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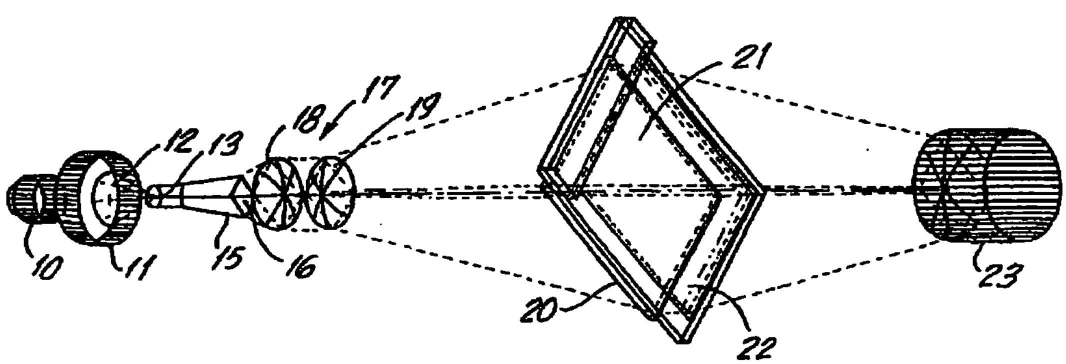

(57) Abstract

A projector system includes a lamp (10), a reflector collector optic (11), relay optics (18, 19) to image light from a light pipe (15) exit pupil to an image gate of an image forming means (21), such as a film gate or an LCD panel. The light pipe is hollow and has cold mirror reflecting internal walls, is tapered in shape, and has an entrance pupil which is larger than a center section in cross section. The light pipe mixes the light by internal reflection and produces light which is uniform in color and intensity across the exit pupil.

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PROJECTOR SYSTEM WITH LIGHT PIPE OPTICS

Field Of The Invention

The present invention relates to optics and more particularly to the light engine of an optical projector system.

Background Of The Invention

At the present time optical projector systems are widely used in business, educational and consumer applications. For example, slide and motion picture projectors are used to show images from film on screens; projection TV may use one or three LCD panels (Liquid Crystal Display) (LCLV-Liquid Crystal Light Valve) and other projectors may use a computer-controlled LCD. The light for projector systems is provided by a "light engine" which generally consists of a light source, for example, a light bulb, a reflector and one or more lenses to direct the light on the "image gate" such as an LCD panel or film gate. In general it is desirable that the light engine have the following characteristics: (1) the light it provides should be bright; (2) the light engine should not produce heat in excess of its ability to be cooled, for example, by a fan, in order to conserve the life of its bulb and other components; (3) it should produce white

light without color spots, which is especially a problem in metal halide arc lamps; (3) the light should be spread evenly over the image gate. Often, in commercial light engines, the light in the center may be at least 100% but the light in the four corners may be less than 60%; (4) the light engine should be physically as small and as low in cost as feasible.

An improved light engine would spread the light evenly so that the light in the corners of a rectangular image gate ("corner illuminance") is at least 70% of the light at the gate's center; the colors from the lamp are homogenized to produce white light without color spots; and there is reduced wasted light due to "spillage" (light beams which fall outside of the image gate).

In the article "A Uniform Rectangular Illuminating Optical System For Liquid Crystal Light Valve Projectors", Chang et al, Eurodisplay '96, pgs. 256-260, light from a short arc lamp is gathered by an elliptical reflector and transmitted through a RPGR (Rectangular Pillar-Like Glass Rod) to a LCLV (Liquid Crystal Light Valve).

In addition, a number of other articles and patents have described light pipes for projection systems, including U.S. Patents 5,146,248 (column 6, lines 35-51);

4,813,765 (column 1, lines 40-42); 5,696,865 (column 4, lines 61-65); 5,634,704 (column 8, lines 55-58); 5,625,738; 5,059,013; 4,045,133; 3,913,872 and 3,170,980.

A solid light pipe, when used in a projection system to transmit light from a light source to an image gate, presents a number of problems. If the light source produces a large amount of heat, such as an arc lamp, the light pipe may have to be made of Pyrex (TM of Corning) or other high temperature resistant (low thermal expansion) glass. However, the light transmission of such high temperature glass is poor compared to regular optical glass, and consequently light would be lost and the efficiency of transmission of light would be unsatisfactory. In addition, although optical glass or optical plastic appears clear and unblemished to the naked eye, it generally has microscopic sized bubbles and lines. Those microscopic sized imperfections cause an unpredictable and undesirable color shift in the transmitted light.

It may be difficult, or impossible, to meet a typical specification for color uniformity of $\pm$ 200^{o}K due to color shifts caused by the non-homogeneous solid transparent material of the light pipe. Furthermore, a solid light pipe, especially if made from glass, adds to the weight and

expense of the light engine. It requires special mounting, for example, by screws having pointed ends, and the mounting may be delicate and expensive.

An active matrix consists of tiny picture elements ("pixels") which are switched on and off. An organic fluid, called a "liquid crystal", is held between transparent plates. Generally the crystals are transparent but can alter the orientation of polarized light passing through them when the alignment of their molecules is changed by applying an electrical field across the crystals.

In a color LCD having a single plate the two outside faces of the transparent plate are coated with a polarizing filter (sheet polarizer) so that only P (parallel to plane of incidence) or S (perpendicular to plane of incidence) directed light waves may pass. Each full color pixel comprises a red, green and blue subpixel which has color filters so that only red, green or blue light is transmitted. In a normally open panel, when no power is applied, light incident on the first polarizer is plane polarized along a chosen plane. The liquid crystals, with no power on, are aligned to twist the polarized light through 90°. The second polarizer/analyzer is set at 90° to the first one. In this manner, light is transmitted along a single polarization plane through the panel when

there is no power on. Most LCD projection panels are of this type. When a pixel (or sub-pixel) is activated through the application of an electric field (power on), the polarized light will not be twisted by 90^{o} by the Liquid Crystal and will therefore be blocked by the second polarizer/analyzer.

The active matrix consists of one transistor for each subpixel, formed directly thereon, and the connecting printed wires. The wires are generally formed in column addressing lines and in row addressing lines. The polarized light is derived from a non-polarized light source, such as a bulb. Due to the filtering, only one-half of the light output of the light source is utilized.

It is desirable, in many LCD projector systems, that all of the light be utilized. This would result in a brighter picture, using the same size of bulb. Alternatively, the bulb size may be reduced, which reduces the heat generated by the light engine. A smaller bulb may be cooler and may have a longer life. It has been a major goal in the LCD projection industry to develop ways to recover part of the light in a projection system that is not polarized in the required polarization plane. Such light is lost from the projected beam. If successful, such

a device, called a "polarizer doubler", will double the overall light efficiency of a projection system to greatly improve a projector's performance-to-cost ratio.

A number of prior patents and articles have suggested that the unpolarized light may be separated into two polarized beams, the polarization of one of the beams reversed and the two beams combined. That type of system is called a "polarizer doubler" as it doubles the amount of light available in one polarization. Such a polarizer doubler generally uses a Polarizing Beam Splitter (PBS) which separates light into its two polarizations.

Polarizer-doubler systems for LCD panels are disclosed in U.S. Patent 4,913,529; U.S. Patent 5,601,351; European P.A. 0467-447-A1; U.S. Patents 4,798,448; 5,566,367; 5,653,520; and in the following articles: Nicholas et al, "Efficient Optical Configuration for Polarized White Light Illumination of 16/9 LCDs in Projection Display", Japan Display '92, pgs. 121-124; Shikama et al, "A Polarization Transforming Optics For High Luminance LCD Projector", Japan Display '93, pgs. 26-29; Imai et al, "A novel polarization converter for high-brightness liquid crystal light valve projector", Euro Display '93, pgs. 257-260 and Japan Display '93, pgs. 235-237; and DeVaan, Brandt, "Polarization conversion system LCD projection, Euro-

Display 1995, pgs. 253-256. U.S. Patent 5,777,789 discloses a light tunnel with straight sides and a polarizing beam splitter (PBS) which is not a doubler.

The above-cited patents and articles are incorporated by reference.

Summary Of The Invention

In accordance with the present invention there is provided a novel and improved light engine for projector systems. The projector system may include the following conventional portions: a light source, such as an arc lamp, a reflector, relay optics such as one or more lenses, an image gate such as a film gate or LCD panel, and a projector lens alone or with field optics. The light engine includes the lamp, reflector and relay optics. In addition, the present invention provides a novel collector-reflector assembly which forms the light from the reflector into a cone, instead of another beam shape, and a tapered light pipe LPI (Light Pipe Integrator). The collector optic is formed as a continuous mirror curved surface. That surface comprises two, or more, ellipses having different eccentricities (e) and focal points (F). The ellipses are in profile (cross-sections in planes through the reflector's optical axis); but cross-sections of the reflector perpendicular to its optical axis are

circles. The truncated end of the light cone is positioned on the entrance pupil of the light pipe. The relay optics are positioned between the exit pupil (exit face) of the light pipe and the image gate. In some embodiments the relay optics may be omitted and the exit pupil may be positioned directly proximate the image gate.

The light pipe integrator (LPI) functions on the principle of internal reflection. The entrance pupil (entrance face) of the light pipe receives the conical beam from the collection optic (reflector). The entrance pupil is flat and round, or octagonal, in a cross-section perpendicular to the optical axis, to best match the truncated cone shape of the light beam. The exit pupil (exit face) of the light pipe is flat in a cross-section and has the shape and aspect ratio of the rectangular image gate, for example, the LCD panel. This aspect ratio is typically 4:3, although other aspect ratios may be utilized, such as HDTV's (High Definition Television) image gate aspect ratio of 9:16.

The light pipe integrator integrates the colors from the arc lamp and produces a homogenized, uniform color temperature for white light at its exit pupil. The light pipe also provides a rectangular exit face that may exactly fit the image gate aperture or Polarizing Beam Splitter (PBS) (aspect ratio and shape), thus substantially reducing

the amount of light lost in spillage. The light pipe gives an excellent distribution of light over the image gate or input face of the PBS. The light engine consequently produces a beam at the image gate, easily resulting in corner illuminance (ANSI) of 70% of center, which is a major image quality enhancement over presently commercially available light engines. The light pipe, and the multiple-ellipse reflector (collector optic), called "VAREX" (TM of Torch Technologies LLC), improves color uniformity, light uniformity and collection efficiency.

The cone angle distribution ("angle population") of the incoming light cone from the light source sets the cone angle distribution of the outgoing cone. It is desirable that the outgoing beam cone angle be reduced. The goal is to match the required angle population of the image gate, i.e., the LCD. The preferred shape of the light pipe (LPI) is composed of an entrance tapered section, a narrow center section and an exit tapered section. The wide part of the taper of the exit tapered section is toward the image gate. The entry tapered section has the wide part of the taper facing the light source. Such a double tapered light pipe produces a reduction in the angle population of the outgoing beam cone and reduces the geometric extent, which results in the reduction of the physical length of the light engine.

A preferred embodiment of a light pipe LPI is a hollow light pipe with a two tapered section shape, an entry pupil, a center section, which is square, or an octagon in cross-section, and a flat rectangular exit pupil of the chosen aspect ratio.

The preferred light pipe integrator (LPI) functions on the principle of internal reflection. It is hollow with mirror interior walls (internal reflection) and is not a solid piece of glass or other transparent material (total internal reflection). The interior walls of the LPI are coated with a "cold mirror coating." That coating is reflective (mirror) to visible light but passes IR (Infra Red) light; which is undesirable heat. The LPI is formed of flat sheets of metal or heat resistive low thermal expansion glass. The flat sheets permit an even high-quality cold mirror coating, which is expensive or impossible on curved glass. The light pipe provides color uniformity which has been measured at $\pm 50^{\circ}K$.

The present invention provides a polarizer doubler for rotating a rejected linearly polarized beam by 90°. Its polarization axis is oriented in the same direction as the polarization axis of the selected beam. In one embodiment, the two beams are then joined side-by-side (not superposition of beams). It uses a Polarizing Beam Splitter (PBS) to collect the entire initial beam (less

reflective and transmissive losses) and directs it through the LCD image plane (LCD image gate) and further onto the screen. In another embodiment the polarizer doubler PD is within the LPI.

There are unique major advantages in using the combination of a PD and an LPI, namely: (1) The beam cross-sections are shaped appropriately for the particular aperture at the image gate, which is rectangular A rectangular beam is propagated, making the beam addition (recombination) more efficient and optically easier to accomplish; (2) The collector/LPI combination can be designed to minimize the cone angle of the beam of light incident on the LCD, thus enhancing the LCD's performance; (3) This optical approach will reduce cost and size of the light engine. These three factors combine to make the light throughout for the projection system more efficient. The gain due to the polarizing doubler is close to a factor of two.

Brief Description Of The Drawings

In the accompanying drawings of the present invention, the figures are described as follows:

Figure 1 is a perspective view of the projector system of the present invention;

Figure 2 is a top view of the projector system of Figure 1;

Figure 3 is a perspective view of one embodiment of a light pipe of the present invention;

Figure 4 is a perspective view of a second embodiment of a light pipe of the present invention;

Figure 5 is a perspective view of a third embodiment of a light pipe of the present invention;

Figure 6 is a side cross-sectional view of a lamp and reflector;

Figure 7 is a side view of another embodiment of a projector system of the present invention;

Figure 8 is an enlarged side view of the entrance portion of a solid embodiment of the light pipe;

Figure 9 is a polar coordinate system showing two collector optic (reflector) for elliptical conic sections having the same focus F but different eccentricities (solid and dash-dash line). The second focal points are F' and F_1'.

Figure 10 is a chart plotting eccentricity (e) of elliptical curves of a reflector (x axis) against magnification (y axis) for five various collection angles (L_I) from 0° to 110°;

Figure 11 is a chart plotting eccentricity (e) (y axis) from 0 to 1.00, against convergence angle (i_E) (x axis) from 0° to 50° for three collection angles (i_I at 40°, 90° and 120°), for a half-cone;

Figure 12 is a chart plotting convergence angle (i_E) (y axis) against collection angle (i_I) at seven eccentricities of elliptical curves from e=0.60 to 0.90;

Figure 13 is a chart plotting converging zone f# (at $i_E = 120^\circ$) (y axis) against magnification (x axis) at two collection angles ($i_I = 60^\circ$ and $i_I = 40^\circ$);

Figure 14 is a cross-sectional view of a light pipe (cross-sections perpendicular to optical axis and the same size). It shows a simplified diagram of a light cone entering the entrance pupil of the light pipe integrator (hollow, mirrored interior walls);

Figure 15 is a chart plotting the length of the light pipe required for the first reflection in mm (y axis) against the angle of convergence (alpha) (x axis) from 0° to 50° for the three diameters (d) of Figure 14;

Figure 16 is a simplified cross-sectional diagram of the tapered light pipe of the present invention (hollow) having circular cross-sections;

Figure 17 is a chart plotting the ratio of the areas of the entry pupil : exit pupil $\left(R_D = \frac{D_p}{D_c}\right)$ (y axis) against ratio of cone angle f#s $\left(R_f = \frac{f_p}{f_c}\right)$ (x axis) where p is the exit pupil having a rectangular shape in the ratio 4:3 and c is the entry pupil having a round shape;

Figure 18 is a chart plotting the f number at the exit pupil (1.0-6.0) (left scale) at various f#s (1.0 to 2.0) of an LPI (Light Pipe Integrator) (y axis) against the exit pupil diagonal size in mm (x axis) for an entry pupil round in shape and 16 mm diameter (D_c);

Figure 19 is a side cross-sectional view of an embodiment of the LPI;

Figure 20 is a perspective view of a tapered and hollow LPI having an octagonal entry pupil and a rectangular exit pupil;

Figure 21 is a cross-sectional profile view of a multiple eccentricity e set of elliptical curves forming a continuous surface to provide a constant magnification;

Figure 22 is a cross-sectional profile view of a double eccentricity elliptical curve;

Figure 23 is a side view of a light engine using a U-shaped curved LPI;

Figure 24 is a perspective view of a double-lamp light engine for use with a motion picture film gate;

Figure 25 is Table 1;

Figure 26 is a side cross-sectional view of a double-tapered LPI;

Figure 27 is a perspective view of a double-tapered hollow LPI having a square entry pupil and a rectangular exit pupil;

Figure 28 is a side view and Figure 29 is a cross-sectional view, along A-A of Figure 28, of a metal casing for the flat cold mirror sheets forming the light pipe of Figure 27;

Figure 30 is a cross-sectional view of the system of the present invention exemplifying the use of its novel optics to provide a polarization doubler;

Figure 31 is a side view of a PBS, 1/2 wave retarder assembly;

Figure 32 is a cross-sectional view of the doubled beam on the LCD plate having an aspect ratio of W:H;

Figure 33 is a cross-sectional view of the beam as it exits the exit pupil of the LPI and having an aspect ratio of W/2:H;

Figure 34 is a perspective view of an LPI having an octagonal entry pupil and a rectangular exit pupil with an aspect ratio of W/2:H;

Figure 35 is a cross-sectional view of an embodiment using a solid LPI;

Figure 36 is a top view showing a PD (Polarization Doubler) having equal path lengths for the P and S components and using mirrors;

Figure 37 is a side view of a PD using different focus points to obtain the effect of equal path lengths for the P and S components;

Figure 38 is a side view of a PD using a convex lens to obtain the effect of equal path lengths for the P and S components;

Figure 39 is a side view of a PD using a concave-concave mirror to obtain the effect of equal path lengths for the P and S components;

Figure 40 is a side view of a PD using a glass prism in one component path to obtain equal path lengths for the P and S components;

Figure 41 is a side cross-sectional view of a PD;

Figure 42A is a side view of a polarizer doubler;

Figure 42B is a front view of a polarizer doubler of Figure 42A;

Figures 43A-43C are side cross-sectional views of polarizer doublers within a light pipe, the Figures 43A-43C showing alternative embodiments;

Figure 44 is a side cross-sectional view of the polarizer doubler of Figure 42A positioned at the exit pupil of a light pipe; and

Figure 45 is a side cross-sectional view of the polarizer doubler of Figure 42B positioned within a light pipe.

Detailed Description

As shown in Figure 1, the first embodiment of the light engine of the present invention is used in an LCD (Liquid Crystal Display Projector System). That projector system includes an arc lamp 10 and reflector 11. The reflector 11 (collector assembly or collector optic) forms the light into a conical beam 12 (cone) having a peak (tip) 13. The beam is directed so that the cone peak falls within the entrance pupil 14 (entrance face) of a light pipe 15 - LPI (Light Pipe Integrator). The light exits from the exit pupil 16 (exit face) of the LPI 15 and is transmitted through the relay optics 17 consisting of first plano-convex lens 18 and second plano-concave lens 19. In some cases a field lens is used between the image gate and the projection lens. Those components form the light engine.

The relay optics 17 directs the beam onto the image gate (entry face) of an LCD panel 21. The LCD panel 21 is preceded in the optical path by a Fresnel lens 20 (Fresnel lens sheet) and is followed by a second Fresnel lens 22. A projection lens 23 focuses the image from LCD panel 21 onto a screen (not shown). A "Fresnel lens" is a plate having concentric grooves (about 40-300 grooves per inch) which is molded as a thin plastic sheet and replaces the curved surface of a conventional lens.

A light pipe (LPI) is an elongated optical element having an entrance pupil, reflecting internal walls and an exit pupil. Light entering the entrance pupil is internally reflected to become homogenized (mixed). The LPI is preferably hollow with internal mirror walls. Alternatively, the light pipe may be a solid transparent member of optical glass or plastic whose outside walls should not be mirrored because it would lose its total internal reflective property. The solid light pipe is held in place by a knife edge or plastic screw supports and covered (not touching) by a sheath, for example, a sheet metal sheath.

The entrance pupil 13 is preferably square, cone-shaped or hemispherical (if solid LPI) or flat and round or octagonal (if hollow LPI) in a cross-section perpendicular to the optical axis to accord with the shape of the light

beam cone. If the LPI is solid the beam cone is truncated perpendicular to its axis of rotation in the case of a flat entrance pupil. The light pipe exit pupil 16 is flat and rectangular and of the same aspect ratio as the aspect ratio of the image gate, typically 4:3 for LCD panels.

The light pipe section closest to the LCD panel is tapered so that the exit pupil is at least 50% larger (in area) than the center section of the light pipe (except if using a PBS) and the light pipe becomes larger (in cross-sections perpendicular to its optical axis) towards its exit pupil, i.e., toward the image gate. This tapered shape permits an efficient transmittal of the light without wasting light, due to spillage, at the image gate. Preferably the ratio of the entrance pupil area to exit pupil area is in the range of 1:1.5 to 1:5 and most preferably in the range of 1:2 to 1:4. Preferably the cross-sectional area of the exit pupil is at least 50% greater than the cross-sectional area of the center section.

In the embodiment of Figure 3 the light pipe 25 has a round and flat entry pupil 26 and a rectangular and flat exit pupil 27, both of which are flat perpendicular to its optical axis 28 (dash-dot line). The aspect ratio (Width : Height) of exit pupil 27 is typically 4:3. The light pipe 25 at the entrance pupil 26 is round and its walls

gradually become flat. The light pipe 30 of Figure 4 is similar, except its walls are parabolic in shape, i.e., the walls are parabolic in cross-section profiles taken in planes through the optical axis 28.

One embodiment of a light pipe 31 is shown in Figure 5. In that embodiment the entrance pupil profile 32 is curved and the exit pupil 33 profile is flat and rectangular in cross-section.

In the solid LPI embodiment of Figure 19, for example, the diameter "q" is 14 mm and the height "p" is 24 mm and the exit pupil width is 18 mm. An entry portion 35 is round (in cross-sections perpendicular to the optical axis). The round entry section 35 extends for at least one-third, and preferably about one-half, of the length of the light pipe. The hemispherical profile entry pupil 32 receives a conical beam. In Figure 19 the entry pupil profile 32a is cone-shaped.

Hollow LPIs are preferred to solid transparent LPIs for a number of reasons. Costs are reduced because the hollow LPI may use flat, reflective coated material that is mechanically easy to assemble and integrate into the "light engine" system. There are no problems with entrance and exit pupil losses (no AR coatings needed), or heating of the glass substrate. Sheet metal or low thermal expansion (high temperature resistant) borosilicate glass can be used

as a reflector substrate (the base for the internal reflective walls). The light travels through empty air space without scattering or other interference.

The internal reflective coating is preferably a cold mirror coating to remove IR (Infra Red) heat from the light beam. The removal of IR heat radiation from the beam of light, without the requirement of using transmissive heat filters that reduce substantially the visible light in the beam, is a major advantage. The LPI is formed from flat sheets of metal or low expansion glass having a cold mirror coating on its internal surface. Such coatings are more difficult and expensive to apply to a curved substrate (curved glass base).

An LPI has been fabricated and tested using a cold mirror coating (HR98C) manufactured by Optical Coating Laboratories Inc. (OCLI) of Santa Rosa, California. It has a reflectivity of 98.5% average over the visible spectrum. Such coatings are typically used in flat mirrors and are designed for a specific angle of incidence (such as normal or 45 degrees). One gets a color shift in the reflected light if the incident light is more than +/-15 degrees off the design angle for the coating. This cold mirror coating (a multilayer or dielectric coating) in an LPI makes the angle of incidence dependence of the coating not critical. One of the major properties of the LPI is the

"homogenizing" of the colors within the LPI, so by the time the beam exits from the LPI the various colors are well mixed and color uniformity is excellent.

A suitable cold mirror coating will transmit 90% of the IR light and reflect at least 98% of the visible light. A ray having both IR and visible light and which is reflected twice in the light pipe will lose at least 90% of its IR heat and be reflected with a loss of less than 4% of visible light.

Preferably, as shown in Figure 27, the flat glass cold mirror sheets 130 are sheet metal and form a sheet metal case 131. The case is the V-BLOCK light pipe and acts as a heat sink. It may be cooled, if required, by a fan.

It is believed that as much as 95% of the heat of the beam may be removed by passing through the cold mirror glass and into the metal casing. Another advantage of a cold mirror coating on the LPI is that if one takes heat out via a "cold-mirror" coating on the reflector, the huge variation in angle of incidence results in losses of visible light. Of course, that is also possible to some degree in the V-block LPI, but the angles are not so bad.

The metal casing may be sheet metal with fins and may be die cast, also with fins. If the lamp is small the heat may be removed by convection air, for example, through holes in the bottom and top of the projector casing. The

metal housing of the LPI acts as a heat sink and permits novel forms of projector cooling to avoid noise, weight and unreliability of a conventional cooling fan.

The metal LPI casing may be cooled by thermoelectric cooling, e.g., Peltier effect, using a solid state semiconductor N and P junction, see U.S. Patent 5,724,818, incorporated by reference. Such solid-state thermoelectric cooling is not suitable for a battery operated projector, due to its electrical inefficiency. However, it may be used with a plug-in (household current) projector. The heat from the opposite end of the Peltier effect electrocouples may be removed by a heat sink, i.e., a metal plate with fins, or by convection air or by a fan.

A preferred hollow LPI shape has an octagonal or square and flat (cross-section) entrance pupil, with a tapered first section ending in an octagon or square (cross-section). That octagon or square is attached to a second section (center section) with a rectangular cross-section (14 mm x 14 mm) and a larger exit pupil cross-section (exit section) to match the shape of the PBS or image gate, as shown in Figure 26. The overall length is 106 mm and the entrance pupil is 28 mm in diameter and the exit pupil is 18 mm high and 24 mm wide.

A preferred arc lamp bulb and its reflector is shown in Figure 6. The reflector 70 (collector optic) is metal with a mirror interior finish and its profile is elliptical in shape (17.27 mm F (center), e = 0.746, and may be "tilted ellipse", e.g., two elliptical sections that do not form a single ellipse. The lamp bulb 71 is a plasma arc bulb, for example, type HTI 404W/SE by OSRAM. The light source may be a xenon arc lamp or an incandescent source such as a halogen lamp. The reflector diameter "A" is 3.250 inches (82.55 cm).

The embodiment of Figure 7 shows a configuration of the light engine 50, but the relay lens component is eliminated. The LCD panel 51 is placed at the exit pupil of the light pipe 52 with a field lens 53 between the light pipe and the panel. A field lens could also be positioned in position 53a, following the image gate, or two field lenses could be used one in position 53 and one in position 53a. The design of the projection lens 56 will have to match the choice of the field optics. In this configuration, the light pipe exit pupil is of the same general size as the image gate, i.e., a film gate or an LCD panel. The plasma arc lamp 54 and reflector/collector 55 may be of the type of Figure 6. The system also includes a conventional projector lens 56 and screen 57. This configuration is effective for smaller image apertures,

under three inches in diagonal. The elimination of the relay optics results in tighter packaging (shorter length) for the projector. There is a substantial reduction in the length of the light path.

Although the description set forth above is in connection with an LCD panel, the invention is also applicable to film projection systems. The following light engine may be used in a film projection system: a light engine comprised of (a) a plasma arc lamp (or halogen lamp), (b) a collector optic, (c) a light pipe integrator, (d) relay optics, (e) field optics, (f) a slide projector film gate or a motion picture projection film gate or an overhead projector stage, and (g) a projection lens.

The shape of the reflector (concave mirror) which gathers the light from the lamp and directs it at the entry pupil of the light pipe is preferably curved with two elliptical sections. It is a concave reflector whose back end (closed end) is formed as an ellipse having a first eccentricity and secondary focal point F_1' and whose front end (open end) is an ellipse having a second (and different) eccentricity and secondary focal point F_2'. This variable ellipse reflector does not form a sharp image (point or line focus) at a focal point, since it is not used to form an image. Instead, it forms a fuzzy ball of light located at, or within, the entrance pupil of the

tapered light pipe. The internal mirrored reflecting surface, in profile, is a nonspherical continuously curved surface having two, or more, difference generators of curvature (preferably ellipses) and in which the cross-sections are circular (perpendicular to the optical axis of the cone of light).

A typical (prior art) collector optic is an elliptical conic section that collects the light from the lamp and directs it to the entrance of the light pipe. Figure 9 shows such a collector and defines the various angles of importance. The angle i(I) is the collection angle (the angle over which light is collected and directed with the lamp at F, the primary focus, taken as the center); the angle i(E) is the convergence angle (the angle of reflection relative to the optical axis of a light beam on the reflector); F' and F'_1 are the secondary foci of the two elliptical sections of the collection optic, using the same primary focus F but of different eccentricities.

A parametric study has been made of the elliptical collector and a number of insights established related to its functioning in conjunction with the LPI. For an efficient collection of light from an arc light source it is required that the collection angle i(I) sweep through between 35 and 135 degrees. This angle sweep may not be mechanically or otherwise attainable for each application,

so the analysis considers a more modest collection angle sweep between 40 and 120 degrees although, when conditions allow, a collection angle between 35 and 135 degrees should be implemented. Eccentricities of the ellipse between e=0.60 and e=0.90 are investigated. Most practical applications would fall in the range of e=0.60 to e=0.75. This does not mean that special circumstances may not indicate the use of eccentricities outside this range.

With the collection angle limited to 120 degrees, parametric plots are made for the magnification vs. eccentricity at various collection angles (Figure 10) and the converging angle vs. eccentricity at various collection angles (Figure 11). A plot of convergence angle vs. collection angle at various eccentricities is shown in Figure 12. The following conclusions are drawn:

1. The collector maximum convergence angle at the collection angle of interest (120 degrees) is solely dependent on the eccentricity of the ellipse. This is the maximum convergence angle that a LPI will see.

2. The magnification of the focal spot depends also primarily on the eccentricity of the ellipse, at various collection angles.

3. Since the convergence angle gets bigger as the focal length of an ellipse becomes smaller, an optimization decision is made when matching a collector optic with an

LPI. A small spot at a small convergence angle is desired. Figure 13 shows a plot of the converging cone f# (focal number) as a function of the magnification.

4. The light coming out from the back end (closed end) of the elliptical reflector has the smallest convergence angle and the highest magnification. The light coming out from the front end (open edge) of the reflector has the highest convergence angle and the smallest magnification.

5. The light coming out of the arc lamp is fairly evenly distributed within the collection angle sweep between 35 and 135 degrees.

A constant cross-section hollow LPI is shown in Figure 14A only for the purpose of explanation. A beam of light includes angles of incidence of a (alpha) and b (beta) represents the input from an elliptical collector optic. The smaller angles b will obtain their first reflection, within the light pipe wall, further down than the larger angles a. The larger angles a will have more reflections as they travel down the LPI. The distance down the LPI for the first reflection of an incident ray at various angles of convergence a (alpha) for a number of sizes LPI openings d are depicted parametrically in the plot shown in Figure 15. Subsequent reflections after the first reflection will occur down the LPI every 2x (twice the distance from entry pupil to the first reflection). In Figure 16 O (theta) is

the angle of convergence. The angle a (alpha) represents a small angle of convergence and the angle b (beta) is the largest angle of convergence from the reflector. x is the initial principal ray's first reflection distance in the LPI; 2x is the distance for its second reflection; and $\tan a = \frac{d}{2}/x$ and $x = d/2 \tan \theta$.

A tapered LPI is shown in Figure 16 with the wider portion toward the film gate. Principal rays coming in at the entry pupil (smaller end) exit at the exit pupil (larger end) at a smaller angle. The angle of the incident ray (e.g. a or b) is changed each time it is reflected from the wall of the LPI by O (theta). A tapered light pipe is used to change the f# of the incident beam to a larger f#, thus reducing the angle population maximum value at the exit of the light pipe. This is an important advantage of the tapered LPI. Figure 17 is a plot relating the ratio of the diagonals of a circular entry pupil and rectangular exit pupil of a tapered light pipe of the ratio of the f#s at its entry and exit pupils. Figure 18 is a parametric plot of the light pipe diagonal vs. the exit pupil cone angle for an entry pupil diagonal of 16 mm, based on a circular entry pupil and a rectangular exit pupil.

The following conclusions apply from this study:

1. The incoming light cone from the elliptical collector optic spans a range of convergence angles, from about 6 to 45 degrees, and has a variety of spot sizes. Preferably the LPI optic uses double-taper sections shown in Figure 26. The larger entry pupil, due to the entry section taper, enables the LPI to gather the larger spots (at the lower angles) while not adversely affecting the smaller spots (at the higher angles).

2. The LPI integrates the incoming light beam in terms of color and light distribution at the exit pupil of the light pipe (mixing) by a number of reflections inside the light pipe, both for the smallest and largest incident angles.

3. The LPI shapes the beam so that the output LPI cross-section (exit pupil) is the same shape and aspect ratio as the aperture (image gate) to be illuminated. The entry pupil of the LPI is fitted to a round cross-section incoming beam, i.e., a conical beam.

The LPI changes the f# of the cone angle of the angle population between the incoming beam and of the outgoing beam. The "angle population" is the percent of total beam per angle increment, i.e., if the light is 80% at angles less than 6 degrees it has a low angle population. This is important because the LCD panel angle population acceptance angle is rather limited (under 10 degrees). The tapered

shape of the LPI reduces the maximum angle of the incoming angle population and produces an outgoing light beam having a low angle population (at least 80% is under 10 degrees).

The goals of the LPI based light engine are to provide the maximum possible amount of light that can be collected from the arc lamp through the image gate (open aperture) where the LCD panel is located at the proper angle population. The angle population should be limited to $\pm$ 15 degrees, and is preferably within $\pm$ 10 degrees, and is most preferably $\pm$ 6 degrees.

The choices involving the collector optical element, an ellipse, are between a small spot and a small convergence angle, which are incompatible. An ellipse in the eccentricity range between e=0.65 and e=.75 is chosen in conjunction with a light source 3 mm long (the arc gap is 3 mm). This range of eccentricities provides small spots and relatively large convergence cone angles. The higher eccentricity end (e=.75) is dictated by the magnification that can be tolerated (arc gap 3 mm). For example, at a collection angle i(I) of 40 degrees the magnification at e=0.75 is approximately X6. A 3 mm arc gap will be imaged into an 18 mm spot. At e=0.60, it will be imaged into an 11 mm spot. The maximum angle of convergence for e=0.75 is 28 degrees and for an e=0.65 it is 41 degrees. The maximum of the converging angle is dictated by the number of

reflections in the light pipe one can tolerate (the sharper the angle the more the number of reflections), and the limit imposed by the critical angle of the medium of the light pipe medium.

One of the problems with the tapered LPI, and other LPIs, is that some of the small angles coming into the LPI will not reflect even once and go through unmixed. This adversely affects the color uniformity and the light distribution on the screen. For this reason, and to optimize the LPI performance, one LPI configuration that optimizes the LPI functions listed above is shown schematically in Figure 5. It is a hollow LPI. The center section is narrow and has a constant cross-section round in shape. The first section is the mixing section for the incoming cone. The entrance pupil of the LPI has a cone, or quasi-spherical, open entrance. This approach avoids any refractive effects that would tend to reduce the angles to the normal upon entry which would make distances between reflections further apart and therefore require a longer LPI. At the interface between the circular and rectangular light pipe section (the exit section) a number of transition shapes are possible. A preferred shape, easy to fabricate, would require the end of the circular light pipe of the mixing section to become a rectangle of the proper aspect ratio with the same diameter as the light pipe.

This, then, would be mated to the small end of the tapered section of the light pipe whose purpose is to reduce the maximum cone of the exit angle population. The light pipe mixing section should be long enough and with a cross-section small enough where the lowest converging angle of the entrance beam can get at least one reflection inside. Another preferred transition shape for the mixing section of the LPI or, for that matter, for an LPI consisting solely of a tapered section, starts with an octagonal LPI entrance cross-section instead of circular. The octagonal cross-section can make a smooth transition with a rectangular LPI exit cross-section, as shown in Figure 20. This transition geometry is most suitable in developing good corner coverage for the light distribution on the screen.

The fundamental trade-offs involved in the LPI/Collector optic combination are depicted in Figures 13 and 17. Figure 13 details the relationship between the convergence angle (listed in terms of the f#), the magnification and the eccentricity e of the elliptical collector optic. At low eccentricities one obtains low magnification and large convergence angles. At high eccentricities one obtains high magnification and smaller convergence angles. The plot depicts the maximum convergence angle (originating at the edge of the ellipse)

and the maximum magnification (originating at the smallest collection angle of 40 degrees). Figure 17 shows how the ratio of the diagonals for the entrance circular aperture of the LPI and the exit diagonal relate to the change in f#s of the incoming and outgoing one angle populations. Since the LPI exit area is limited to the size of the panel diagonal for small LCD panels (or other open apertures) up to about 3", the smaller the entry diagonal is the better the cone angle populations will be when incident on the panel (i.e., smaller cone angles).

Table 1 (Figure 25) describes the first order approach to optimization. Three typical LCD panels have been selected, 1.3", 2.0" and 3.0" (4:3 aspect ratio). The arc gap size is then chosen. A popular metal halide lamp currently in production is the Osram VIP R 270 which has the smallest arc gap (1.6 mm) available in that power range. It puts out 15000 lumens. Another lamp used in this optimization is an Osram MH lamp 404W/DE with 30000 lumens at 400 watts and an arc gap of 3.0 mm.

With the small gap lamp an eccentricity of 0.75 is chosen as a first iteration. The results listed in Table 1 show that the spot size at the entrance of the LPI has a diagonal of 10 mm. The end result indicates that this choice of arc lamp is a good match for the 2.0" panel; an easy fit with the 3.0" panel and somewhat of a mismatch for

the 1.3" panel. The cone angle population has a maximum of 28 degrees from the ellipse while the acceptable cone to yield an f# of 3.5 at the panel is 20.3 degrees. For the 3.0 mm gap a smaller eccentricity is used to reduce the magnification of the entrance spot into the LPI. The 3.0" panel is a good fit with this eccentricity and arc gap. The other two panels would reject a substantial amount of light that resides in the higher cone angles.

For the situations where there is not a good fit in the cone angle population, a good trade-off would be to lose some incoming light by making the entrance diagonal to the LPI smaller, i.e., allow only a 10 mm entry pupil (aperture) for the 3.0 mm arc lamp. That approach would reject some of the initial spot. However, about 75% of all the light is concentrated within 50% of the diagonal, so cutting the outer edge is not as bad as cutting off some of the converging cone angles. Within the converging cone, roughly 10% of the total light is within each 10 degree collection zone. Preferably a hollow "V-BLOCK" (V-8 INTEGRATOR - TM of Torch Technologies LLC) LPI is used having an entrance tapered section and an exit tapered section, see Figure 26. That device can accommodate both the generated spot size and its cone angle population. The entry tapered section (the entry pupil) collects all the light from the incoming beam. The embodiment of Figure 26

is preferably used with the "VAREX" (TM) reflector having a variable elliptical eccentricity and two, or more, focal points.

One of the limits imposed on the optimization between light source and image aperture is due to the elliptical collector that is defined in terms of a single eccentricity. This is a severe limitation because once one selects the eccentricity, it determines a specific value of the maximum convergent cone angle and the maximum magnification for the spot. The present invention provides a design of elliptical collectors with variable eccentricity. It is desirable to keep the eccentricity of the back rays collected around the 40-degree collection angle at a small eccentricity to reduce magnification. It is also desirable to keep the edge of the ellipse at a collection angle of 120 or more degrees at low eccentricity to reduce the converging cone angle population. An elliptical curve is preferred where the back end starts at a lower eccentricity than the front end. Figure 21 shows a curve with a variable eccentricity derived from equal magnification requirement for all collection angles. The various zones focus at different points along the optical axis, e.g., the interfocal distance for each eccentricity is different. Clearly, such a major change in eccentricity along the various collection angles is not practical.

Figure 22 shows a practical example of a variable eccentricity curve. In this case the spread of eccentricities is limited to 0.05. The different elliptical curves have different focal lengths, within ± 2mm of a central focal point. Even though the two beams focus at different points on the optical axis, the LPI can still collect all the light projected by the collector. The light collected by the elliptical collector need not be focused in a single focal point.

In the variable eccentricity designs an LPI may have a flared entrance to accommodate extra collection capability from the incoming cone of light (Figure 22). For small panels one does not need relay optics and the optical engine configuration can be as in Figure 7. For panels larger than about 3.0" in diagonal, the light engine design will follow the design of Figures 1 and 2.

Figure 26 shows the most preferred embodiment of the LPI. The entry section 100 starts with the entry pupil 101. The entry pupil is flat (cross-section perpendicular to optical axis 102) and may be round or octagonal. This LPI is hollow and constructed from sheet metal mirrors. The entry section is tapered in shape with the larger portion toward the light source (left in Figure 26). In the prototype the entry pupil cross-section is square, but an octagonal cross-sectional entry pupil is preferred. The

entry pupil area (cross-section) is in the range of 1:1.5 to 1:5 and most preferably in the range of 1:2 to 1:4, to the smallest area cross-section (perpendicular to axis 102) of the center section 103. The exit section 104 is also tapered and the exit pupil 105 is flat and rectangular (cross-section). The center section 103 is integral with the exit section 104. In the embodiment of Figure 26, the entry pupil profile is flat and square (28 mm x 28 mm) or preferably octagonal, and if octagonal the entry section transitions to a square flat which is connected to the center section. The entry section is 21 mm long. This embodiment is made of two pieces. At their connection they are both square (14 mm x 14 mm). The second taper (center section and exit section) is 85 mm long and goes from square cross-section (14 mm x 14 mm) to rectangular (24 mm x 18 mm - 30 mm diagonal) to match the aspect ratio of the image gate. Its total length is 106 mm.

The reflector-collector 106 is of the double ellipse type ("VAREX" reflector), described previously, in which the lamp's primary focal points F_1 and F_2 are directed to the secondary focal points F_1' and F_2'; E_1 and E_2 are elliptical curves with the eccentricity of E_2 greater than the eccentricity of E_1, i.e., $E_1 = 0.710$ and $E_2 = 0.730$ and the radius of the reflector goes from 9.0 to 52.3 mm using an OSRAM 404 lamp. When the VAREX reflector is used with

the Figure 26 embodiment ("V-BLOCK") all rays over 6° will have at least one reflection. Typically, the lowest angles are $6-8^{\circ}$. An extra straight square mixing section (center section) between the two tapers may be used for additional mixing, if needed.

Collector optics are positioned with the lamp located on the optical axis. Such optical elements preferably are compound elliptical surfaces (that is, made of variable eccentricities and focal points). Alternatively, one may use a faceted reflector where each facet is directing the local rays in the proper direction towards the LPI element, or a combination of compound and faceted designs. Such designs can be generated by computer programs and fabricated by glass molding techniques, similar to the way automobile headlights are made.

In Figure 23 the LPI (light pipe) is hollow, has an entry section 71 and makes two 90-degree turns with a right angle prism 76,77 at each turn. The entry section 71 has a flat octagonal entry pupil (cross-section) and section 71 gradually changes from octagonal to rectangular in its cross-sections vertical to the optical axis. The entire light pipe 71a makes a 180° turn. The reflector 72 is pointed in the opposite direction from the rectangular face

73 of the LPI 74, which face 73 is proximate an LCD panel 75. In some cases using a turned light pipe may permit a shorter and more compact projector.

In the embodiment of Figure 24 a double bulb system 80 is shown in which, if one bulb ceases to work, the alternative bulb is turned on. The circuit 81, when switched on, will first apply power to the first bulb 82. If it does not light, its dark condition is sensed in milliseconds by circuit 81, as it does not draw power. The circuit then applies power to the second bulb 83. When the first bulb is replaced, the circuit will again apply power to the first bulb. In this embodiment the LPI (light pipe) is hollow and has two branches 84,85, each of which preferably is round or octagonal at its entry pupil cross-section (perpendicular to its turned center axis). The central section 91 of the LPI is rectangular (in cross-sections vertical to the optical axis). A right angle prism 92 is used to reflect the light from branches 84 or 85 into section 91. In addition, a light valve (not shown) may be provided in each branch 84,85 to prevent loss of light when the bulb at that branch is not illuminated. The rectangular face 88 of the light pipe 89 is proximate the film gate 90. This embodiment may be useful in motion picture projectors as the bulbs need be replaced less often.

In Figure 30 of the present invention a "light engine" is shown incorporating a Light Pipe Integrator 3 (LPI) and a Polarizing Beam Splitter 5A (PBS). It is a "polarizer doubler" PD as it doubles the polarized light intensity at the image gate. Light from the lamp 1A (light source) is collected by the collector optic 2A (reflector) and concentrated onto the entrance pupil 23A of the LPI 3A. The LPI 3A transmits the beam of light from its entrance pupil 23A to its exit pupil 26A via multiple reflections. The light exiting the LPI exit pupil and PD is collected by the relay optics 4 (convex-convex lenses) that forms the image of the exit pupil of the LPI onto the image gate, e.g., the LCD plate 7A. The LPI exit pupil is rectangular and, in aspect cross-section, is half the aspect width W of the rectangular LCD plate. In Figure 30 W indicates that width, e.g., this view shows LCD plate 7A on its side.

Preferably, when used with a PD, the light pipe section of the LPI closest to the LCD panel is tapered so that the exit pupil is at least 20% larger (in area) than the center section of the light pipe and the light pipe becomes larger (in cross-sections perpendicular to its optical axis) towards its exit pupil, i.e., toward the LCD plate. This tapered shape permits an efficient transmittal of the light without wasting light, due to spillage, at the LCD plate. Preferably the ratio of the entrance pupil area to exit

pupil area is in the range of 1:1.5 to 1:5 and most preferably in the range of 1:2 to 1:4. Preferably the cross-sectional area of the exit pupil is at least 20% greater than the cross-sectional area of the center section.

Figure 33 shows the cross-section of the beam as it exits the exit pupil of the LPI 3A of Figure 2. Figure 32 shows the cross-section beam as it enters the field lens 6A. The field lens 6A directs the beam onto the rectangular LCD plate 7A and is passed through plate 7A to the projection lens 8A. The width of the beam is doubled as it passes through the PD 5A. PD 5A, in Figure 30, is a half-wave retarder and mirror assembly comprising solid PBS cube 5A and mirror 9A. Both halves of the beam are converted to S-polarization (perpendicular to plane of incidence).

As shown in Figure 30, there is a small gap in the center of the light beam directed and imaged on the image gate. This gap can be eliminated by slightly tilting the PBS cube 5A through a small angle "a" using rotation and/or tilting independently the mirror 9A attached to the PBS cube through rotation of angle "b". Rotation of the PBS cube 5A must be performed while simultaneously all optics along that axis are rotated so that the optical axis alignment between the lamp, collector, LPI, relay optics

and PBS is maintained. The image of the LPI exit pupil formed on the image gate is made of two halves generated by the PBS half-wave plate, mirror assembly. These two halves can be adjusted to have any amount of overlap desired. If the overlap is too bright, it can be diffused using a strip of neutral density filter between the overlap and the field lens 6A.

The functioning of one type of a PBS is shown in detail in Figure 31. Light 30A entering the PBS cube 5A is randomly polarized (unpolarized). The reflected beam 31A has an S-polarization, the transmitted beam 32A has a P-polarization. The cube 5A is not a true "cube" in the sense that all of its faces are squares. Its input face 36A and its output faces 37A and 38A have the aspect ratio 1/2 W:H where W and H are the aspect Width and Height of the LCD panel. For example, faces 36A, 37A and 38A have an aspect ratio of 2:3 and dimensions of 12 mm - Width and 18 mm - Height.

The incoming beam 30A is reflected by the coating 35A which is at a suitable angle to the input face 36A of cube 5A. The coating 35A reflects the S-component of the beam 30A to form outgoing beam 31A and transmits the P-component of beam 30A. The coating 35A may be a multi-layer coating formed by laminating alternating coatings of a high refractive material, such as TiO_2 and MgO, and a low

refractive material,such as SiO_2 and MgF_2, on the face of a right-angle prism which is then cemented to another right-angle prism to form the cube 5A. For example, cube 5A may be of BK-7 glass with a one-half wave coating 35A of MgF 632.8 nm. Alternatively, the coating 35A may be a birefringent adhesive layer, for example, an adhesive of liquid-crystalline diacrylate and a polyamide orientation layer (thickness 50 mm) which is rubbed. A suitable cube 5A (cubic polarizer) is described in connection with Figure 11 of U.S. Patent 2,578,680, and an alternative PBS cube is described at Figure 2 of U.S. Patent 5,570,209, both incorporated by reference. In this case, the P-polarized transmitted beam 32A is passed through a half-wave retarder plate 33A (polarizer rotator) and rotated 90° to line up with the polarization axis of the reflected S-polarized component. The beam 34A which is transmitted through retarder plate 33A has an S-polarization. A half-wave retarder plate 33A may be a layer which is coated, or cemented, on the face 37A of cube 5A, for example, a birefringent adhesive layer on face 37A. For example, the one-half wave retarder plate 33A may be a suitable film on the face of the cube of polyvinyl alcohol, polycarbonate or polystyrene. In principle, one could choose to rotate the S-polarized beam and end up with two P-polarized beams.

In place of cube 5A one may employ a special design of a PBS prism which is a modification of a Glan-Thompson prism. It uses only a thin slab of birefringent material, such as a liquid crystal layer, or a birefringent adhesive layer, between two glass prisms, and is disclosed in U.S. Patent 5,601,351 and the DeVaan article (1995) cited above. That prism operates by total internal reflection and is therefore suitable for all visible wavelengths and has a large angular acceptance. The geometry of the PBS is optimized for LCD projection. The functioning of this PBS prism is considerably improved when used in conjunction with the aconic collector/LPI system disclosed in the present patent application. This improvement relates primarily to the aspect of the invention where the two similarly polarized beams recombine. It is more efficient to recombine two rectangular shaped beams rather than two circular beams, as in the system of the DeVaan article.

Generally the LCD panel (Figure 30) has an aspect ratio of 4:3 (width-to-height). Consequently, the beam from the PBS cube 5A, and its mirror 9A of Figure 30, would have the same aspect ratio of 4:3 and would be rectangular, as shown in Figure 32. The LPI 3A at its exit pupil 26A has a cross-section which is one-half of the aspect ratio of 2:3; however, it may be slightly larger in width to prevent a gap between the side-by-side beams. A high quality large

color LCD panel is 6.4 inches (22.7 cm) diagonal. It has a 4:3 aspect ratio so its dimensions are 5.12" wide and 3.84" high. The exit pupil of the LPI would be .84" wide and 1.26" high. The exit pupil of the LPI is then magnified through the relay optics.

In the embodiment of Figure 35 the LPI 50 is solid (clear glass or plastic) and is integral with one-half of the cube 5A. It terminates in a 45° face 51A which is coated with the coating of face 36, and a 45° prism 52A adhered thereto. This is a low-cost system, although less efficient than a hollow tube LPI. The LCD panel may be an active matrix system, a time-division matrix system, a monochrome panel, a three-color or four-color panel or other type of LCD panel using either S or P polarized light.

A problem with the polarizer doubler embodiment of Figures 30, 31 and 35 is that the two optical paths of the light, after it exits from the light pipe, are not equal. One path, for example S, will be shorter as it goes directly through the cube 5A of Figure 30. The other path P will be longer as it is reflected from the mirror 9A. This has an adverse effect as the beam with the longer path P will be larger than the beam with the shorter path. The

image of the two halves of the light pipe exit will be unequal and consequently will not fit properly into the target area 9A (the LCD plate).

The path lengths are equal in the prism of U.S. Patent 5,601,351, although there will be a loss of light due to the passage of light through the glass, or plastic prism.

A number of alternative optical systems are presented in Figures 36-41 to make path lengths of the two beams equal to each other. These PD embodiments may be used in conjunction with the light pipe embodiments of Figure 30 or with other embodiments of light pipes.

In the PD embodiment of Figure 36 the length of the path of beam S is made longer by reflecting it from several mirrors 50A, 51A. The P beam is converted to S by PBS cube 54A (the converted beam is labeled "CP") and reflected from two mirrors 52A, 53A. The mirror 52A, for CP, is closer to the PBS cube 54A than is mirror 50A, for path S, making the CP and S paths equal over their entire lengths. This embodiment uses a first relay lens 55A, a second relay lens 56A, a light pipe 57A, an LCD plate 58A and a PBS cube 54A of the type shown in Figure 31. Unfortunately, the mirrors may increase the size, cost and complexity of the optical system. In addition, in Figure 36, both beams CP and S

have a long path, which may cause the light in both paths to expand beyond the boundaries of the lens apertures, requiring larger lenses.

In the embodiments of Figures 37 and 38, the mirrors are held in air and are not surfaces on a glass cube or prism. The mirror 63A is a coating, like coating 35A, but which passes the P beam and reflects the S beam and mirror 64A reflects the S beam through half-wave retarder plate 65A.

In the embodiment of Figure 37, P path 61A and S path 62A are made equal to each other in length by placing the focus of P before the LCD plate 60A and the focus of S after the LCD plate 60A.

In the embodiment of Figure 38, a positive lens 70A (convex-convex) is placed in S path 68A. In Figure 39 a negative lens (concave-concave) is placed in P path 66A. The lenses 66A, 67A provide a focus effect which provides the same effective optical effect as equal path lengths for the P and S beams.

In another embodiment (not shown) the angles in the S path are shifted to reduce separation by making a cross-section of the S beam non-round, i.e., an ellipse. This may be accomplished by tilting the mirror in the S path.

In the embodiment of Figure 40, the P path 75A is shortened by having it pass through glass. The S path is reflected from coating 76A, on the top angled surface of glass prism 77A. The P path passes through the glass prism 78A and is reflected by mirror 78A, held in air. The optical path in units of glass is $\ell \times M \cong \ell \times 1.5$, which is 0.5 more than in air, e.g., the optical path through glass has the same effective length as a longer measured path through air. The path lengths Z of P and S should be equal, that is: $Zp = Zs$. If.5 - 2u (units), $\ell = 2/.5u = L/u$, the amount of glass (width of glass) in the path length Zp would be about 4 cm. The coating 76A (reflects S) and mirror 78A (reflects P) are at 45° angles to the beams S and P and a half-wave plate 65A is in the front of mirror 78A to convert the P beam to an S beam.

The embodiment of Figure 41 is another polarizer doubler. It includes a metal housing which holds the four glass sheets in air. The housing is about 9.7 cm long (back to front), 6 cm wide (W), 4.5 high (H), and the PBS is sold by Philips. It divides the incoming unpolarized light beam 81A from the light pipe into two P beams which exit at the exit face 86A of the housing. The path lengths of the two P beams are practically equal. As shown in Figure 41, a beam 81A of random polarized light having an aspect ratio of 1/2 W:H is the incoming beam.

The S component if beam 81 is reflected from the mirrors 82A and 83A which pass the P component. The S component is reflected from the mirror 84A to pass through the one-half wave plate 85A which is held by a metal clip. The P and S components exit the holder face 86A as parallel (upper and lower) bands both with P polarization. The mirrors 82A, 83A and 84A are parallel to each other, and they are angled with respect to the exit face 86A. The mirrors 82A and 83A are similar to coating 35A (Figure 31), except they transmit the P component and reflect the S component. The face plate 86A (Figure 31) is a polarization rotator (half-wave retarder plate) which rotates the S component 90° and converts it into P component.

If the PD of Figure 41 is used, then the exit pupil of the light pipe should match its entry face in size (without a relay lens) and in shape (with or without a relay lens). In the case of an aspect ratio of the image gate, i.e., LCD panel of Width:Height ratio of 4:3 the PD input face (1/2 W) and light pipe exit pupil will have a 2:3 ratio. For example, a light pipe would have an entry pupil which is flat and square (28 mm x 28 mm) and an exit pupil which is flat and rectangular (24 mm x 18 mm).

It is believed that the position of a polarizer doubler within a light pipe is novel because of the expectation that the light pipe, by its reflections, would mix the unipolarized light and cause it to become unpolarized. However, the inventors' experiments and computer analysis indicates that most of the polarized light exiting the PD within the light pipe remains polarized despite its reflections between the output face of the PD and the exit pupil of the LPI.

In the PD embodiments of Figures 44 and 45 the PBS (polarizing filter) comprises two plates 120,121 forming a wedge at a 90° angle to each other, the plates passing P and reflecting S. Two mirrors 124,125, forming wings, are parallel to plates 120,121 and, respectively, reflect S (which had been reflected from plates 120,121) through the one-half wave retarder plates 122,123 (polarizer rotator). Alternatively, and not shown, the two plates 120,121 may instead be four such plates formed as a four-sided pyramid with four mirrors parallel to the four plates and with four retarder plates formed as a frame (front view) around the pyramid.

This type of PD may be positioned at the exit pupil of the LPI, as shown in Figure 44, or within the LPI, as shown in Figure 45. The angles α and B may be varied and the

areas covered by the edge and wings may also be varied. The wing area may be reduced to increase the light per unit area in the wings and aid distribution.

A study was conducted of the usefulness of those polarizer doublers (PD) which increased the geometric extent (GE) with various sizes of LCD panels and various commercially available bulbs (lamps). In general, because available bulbs have a minimum arc gap of 1 mm (Philips UHP-X under development), it was found that an LPI, without a PD, produced more light to small size pixels (1.3 inch diagonal and below) than using a PD. For example, the bulbs UHP 100, UHP 120 (Philips) can be used without a PD for a 1.3 inch panel. However, for larger panels (over 1.8 inches diagonal), the combination of LPI and PD produced the most effective light to the LCD panel.

However, when the PDs of Figures 43A-43C are used within a light pipe, they do not increase the geometric extent. Therefore, those PDs are particularly useful with small panels (under 1.8 inches diagonal).

The embodiments of polarizer doublers of Figures 43A-43C are especially useful when positioned within a hollow light pipe (LPI). Unlike other PDs, they do not increase the cross-sectional area (the geometric extent), e.g., the areas of their input faces are the same as the areas of their output faces. This is especially useful when the PD

is within the light pipe as the light pipe need not double its cross-sectional area (cross-section perpendicular to optical axis) at the PD.

In the embodiment of Figures 43A the light pipe (LPI) 100 is hollow and has a rectangular cross-section 101. The unpolarized light 102 from the LPI entry pupil is polarized into P polarization by the polarizer doubler 103, which consists of angled coated plates 104,105 (PBS-passing P and reflecting S) and one-half wave retarder plate (polarizer rotator) 106 which converts S into P.

In the embodiment of Figures 43C the light pipe rectangular cross-section 101 has an angled PBS plate 110 (polarizing filter) passing P and reflecting S, and a one-fourth wave plate 111 which reflects S and converts it into P.

In the embodiment of Figure 43B a polarizing beam splitter plate 130 (PBS) reflects S and passes P. The S component is reflected from one-quarter wave plates 131,132 which converts S to P. There would be four such quarter-wave plates on the four inner walls of the light pipe rectangular section.

WHAT IS CLAIMED IS:

1. A projector system comprising:

lamp means to generate light;

a hollow light pipe having an entrance pupil, an exit pupil, a center section, reflective mirror internal walls and an optical axis, the light from the collector means being directed on the entrance pupil;

an image forming means to form an image and having an image gate, the exit pupil directing the light on the image gate; and

a projector lens;

characterized in that the light pipe is tapered in shape with the entrance pupil having an area whose ratio to the area of a cross-section perpendicular to the optical axis of the center section is at least 1 to 1.5.

2. A projector system as in claim 1 wherein the lamp means is a metal halide arc lamp having an arc gap in the range of 1-6 mm.

3. A projector system as in claim 1 wherein the light pipe reduces the cone angles of the light from the collector and produces light, at least 80% having cone angles below 10° (half-cone).

4. A projector system as in claim 2 wherein the collector means is a mirror reflector having a central axis and the arc gap is aligned along the reflector's central axis.

5. A projector system as in claim 2 wherein the collector means has a mirror internal wall and is a compound reflector having a profile with at least two elliptical curves having two different eccentricities.

6. A projector system as in claim 5 wherein the reflector is curved and concave in shape in profile and the curvature comprises at least two ellipses having different eccentricities and both eccentricities are in the range of 0.60 - 0.90 and the reflector is circular in cross-sections perpendicular to the axis.

7. A projector system as in claim 1 wherein the light pipe comprises a sheet metal substrate and a cold mirror coating on the mirror internal walls.

8. A projector system as in claim 1 wherein the image forming means is an LCD (Liquid Crystal Display) panel.

9. A projector system as in claim 1 wherein the image forming means is a three-color LCD panel.

10. A projector system as in claim 8 and further including field optics comprising a Fresnel lens means to collimate the light, the Fresnel lens means being positioned between the exit pupil and the LCD panel and a Fresnel lens means to focus the image which is positioned between the LCD panel and the projector lens.

11. A projector system as in claim 1 wherein the entrance pupil cross-section is flat and octagonal and the exit pupil cross-section is flat and rectangular.

12. A projector system as in claim 1 wherein the light pipe has an entry section which is square in cross-sections and is at least one-third of the length of the light pipe.

13. A projector system as in claim 1 wherein the light pipe has an entry section which is at least one-third the length of the light pipe, a center section and a tapered exit section with an exit pupil which is larger in area than the area of a cross-section of the center section.

14. A projector system as in claim 1 and relay optic means to form a cone-shaped beam of light from the collector means and to direct the beam on the entrance pupil.

15. A projector system light engine comprising:

a metal halide arc lamp having an arc gap in the range of 1-6 mm;

a reflector having a central axis, the lamp being positioned at the reflector's axis;

a hollow light pipe having an optical axis, an entrance pupil, a rectangular exit pupil, a central section between the entrance and exit pupils, reflecting internal mirror walls, and a double tapered shape in which the exit pupil and entrance pupil is at least 50% larger than the area of a cross-section of the central section taken perpendicular to the optical axis.

16. A light engine for an optical projector system comprising:

lamp means to generate light;

collector means to collect and direct the generated light;

a light pipe having an entrance pupil, a central section, an exit pupil along a straight optical axis, and reflecting walls; characterized in that

the light pipe is double tapered with the exit pupil being rectangular and the area of the exit pupil and entrance pupil each being at least 50% larger than a cross-sectional area perpendicular to the optical axis of the center section.

17. A light engine as in claim 16 wherein the lamp means is a metal halide arc lamp having an arc gap in the range of 1-6 mm.

18. A projector system as in claim 17 wherein the collector means is an elliptical mirror reflector having a central axis and the arc gap is located at the reflector central axis.

19. A light engine as in claim 16 wherein the light pipe has an optical axis and an entry section which is round or square in all cross-sections perpendicular to the optical axis and is at least one-third of the length of the light pipe.

20. A projector system comprising:

lamp means to generate light;

collector optics means to gather and direct the generated light;

a hollow light pipe having internal mirror walls open to ambient air, an entrance pupil, and exit pupil, reflective internal walls, a center section between the entrance and exit pupils, and an optical axis, the light from the collector means being directed on the entrance pupil;

an image forming means to form an image and having an image gate; and

a projector lens;

characterized in that the light pipe is double tapered in shape with the entrance pupil and exit pupil each having an area whose ratio to the area of a cross-section of the center section is at least 1.5:1 and that the collector optics means comprises a compound reflector having an optical axis, the reflector having a curvature whose cross-sections through the optical axis are segments of at least two different curves.

21. A projector system as in claim 20 wherein the two different curves are ellipses having two different eccentricities and with two different focal lengths which are $\pm$ 2mm from a central focal point.

22. A projector system as in claim 20 wherein the reflector has a mirror internal wall, a back closed end portion having an elliptical curve in profile with a first eccentricity and an open end portion having an elliptical curve in profile with a second eccentricity which is larger than the first eccentricity.

23. A projector system as in claim 20 wherein the light pipe has an entry section having an axis and an entry pupil which is square or octagonal in cross-section taken vertical to the axis and the entry section is at least one-third of the length of the light pipe.

24. A projector system as in claim 21 wherein the elliptical curves each have a different focal point.

25. A projector system as in claim 21 wherein each of the elliptical curves are formed around the same apex point.

26. A projector system as in claim 20 wherein the internal walls are of metal and are flat.

27. A projector system as in claim 26 wherein the mirrors are cold mirrors which reflect visible light and transmit infrared light.

28. An elongated light pipe having an optical axis, an entrance pupil and an exit pupil, for use in a projector system, characterized in that:

(a) the light pipe is hollow and has internal mirror walls and is not filled with a dielectric;

(b) the mirror walls are of metal;

(c) a cold mirror coating is coated on the mirror walls to reflect visible light and transmit infrared light.

29. A light pipe as in claim 28 wherein the entrance pupil is square or octagonal and the exit pupil is rectangular in a cross-section perpendicular to the optical axis.

30. A light pipe as in claim 28 wherein the light pipe is a double tapered shape having a center section and in which the entrance and exit pupils are each at least 20% larger than the area of a cross-section through the center section taken perpendicular to the optical axis.

31. A projector system comprising:

lamp means to generate light;

collector means to gather and re-direct the generated light;

a light pipe having an entrance pupil, an exit pupil, a center section and an optical axis, the light from the collector means being directed on the entrance pupil;

a Liquid Crystal Display (LCD) image forming means to form an image and having an image gate, the exit pupil directing the light on the image gate; and

a projector lens;

characterized in that a polarizer doubler including a Polarizing Beam Splitter (PBS) is positioned within the light pipe or between the light pipe and the LCD image gate and that the light pipe is hollow, not filled with a dielectric, with mirror walls and tapered in shape with the entrance pupil having an area whose ratio to the area of a cross-section perpendicular to the optical axis of the center section is at least 1 to 1.5.

32. A projector system as in claim 31 wherein the polarizer doubler comprises a rectangular input face having an aspect ratio of 1/2 W:H and an output face having an aspect ratio of H:W where W is width and H is height.

33. A projector system as in claim 31 wherein the image gate is rectangular and has an aspect ratio of width W to height H (W:H) and the light pipe exit pupil is rectangular with an aspect ratio of W/2:H and the polarizer doubler is between the exit pupil and the image gate.

34. A projector as in claim 31 wherein the collector means is a reflector with a central axis, mirror internal walls and is a compound reflector having, in profile, at least two elliptical curves having two different eccentricities and is circular in cross-sections perpendicular to the axis.

35. A projector system as in claim 31 wherein the reflector is curved and concave in shape in profile and the profile curvature comprises at least two ellipses having different eccentricities and both eccentricities are in the range of 0.60 - 9.90.

36. A projector system as in claim 31 wherein the polarizer doubler is within the light pipe.

37. A projector system as in claim 31 wherein the light pipe entrance pupil cross-section is flat and either square, round or octagonal and the exit pupil cross-section is flat and rectangular.

38. A projector system as in claim 31 wherein

the hollow light pipe is not filled with dielectric and has an optical axis, a rectangular exit pupil, a central section between the entrance and exit pupils, flat mirror interior reflecting walls of metal or low expansion glass with a cold mirror coating, and a tapered shape in which the entrance pupil is at least 50% larger than the area of a cross-section of the central section taken perpendicular to the optical axis.

39. A projector system as in claim 31 wherein the polarizer doubler has a rectangular input face with an aspect ratio of W/2:H and generates a uni-polarized beam having an aspect ratio of W:H.

40. A projector system as in claim 31 wherein the light pipe is double tapered in shape with the entrance pupil and exit pupil each having a larger area than the area of a cross-section of a center section.

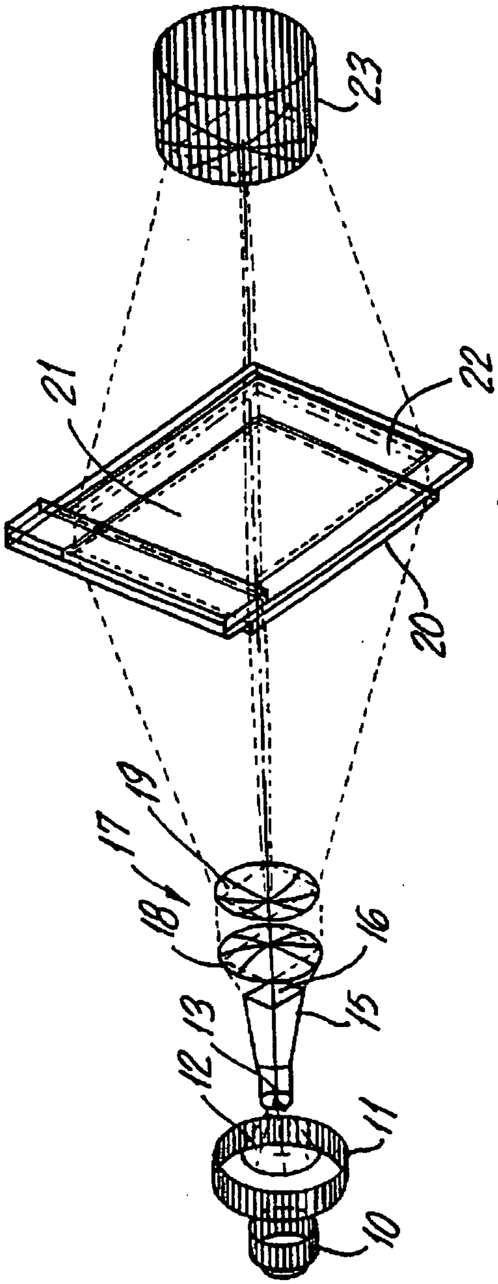

10
11
12
13
15
16
17
18
19
20
21
22
23

FIG.1

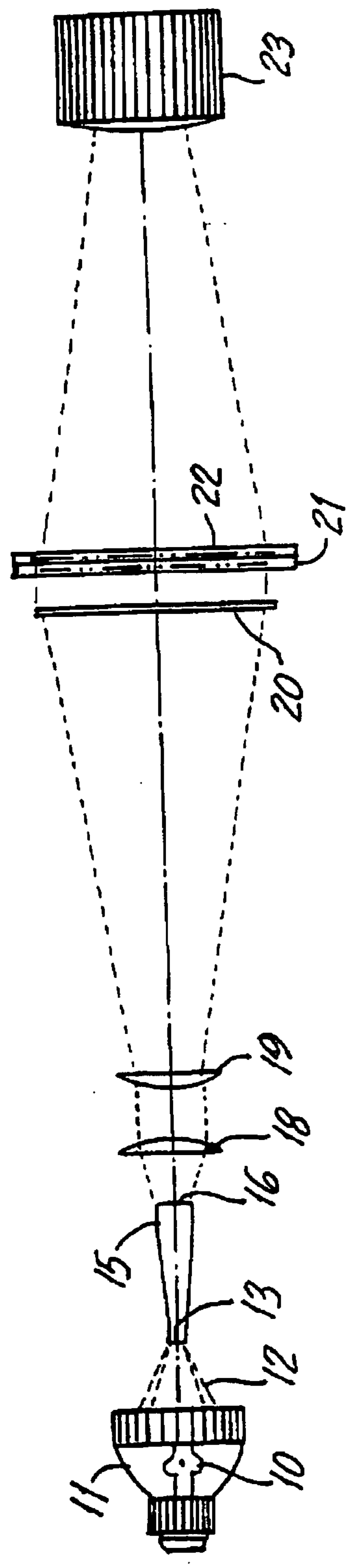

10
11
12
13
15
16
18
19
20
21
22
23

FIG.2

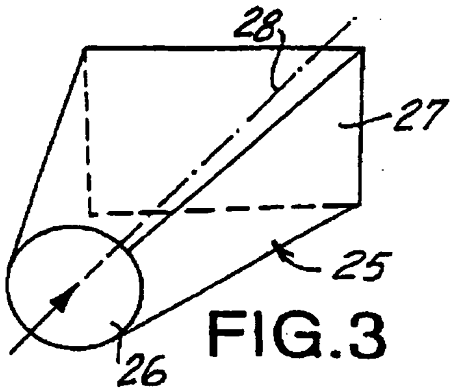


FIG.3

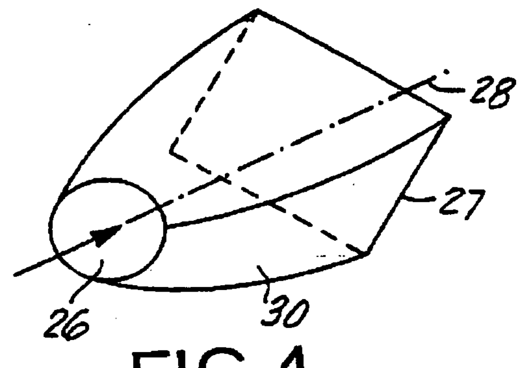


FIG.4

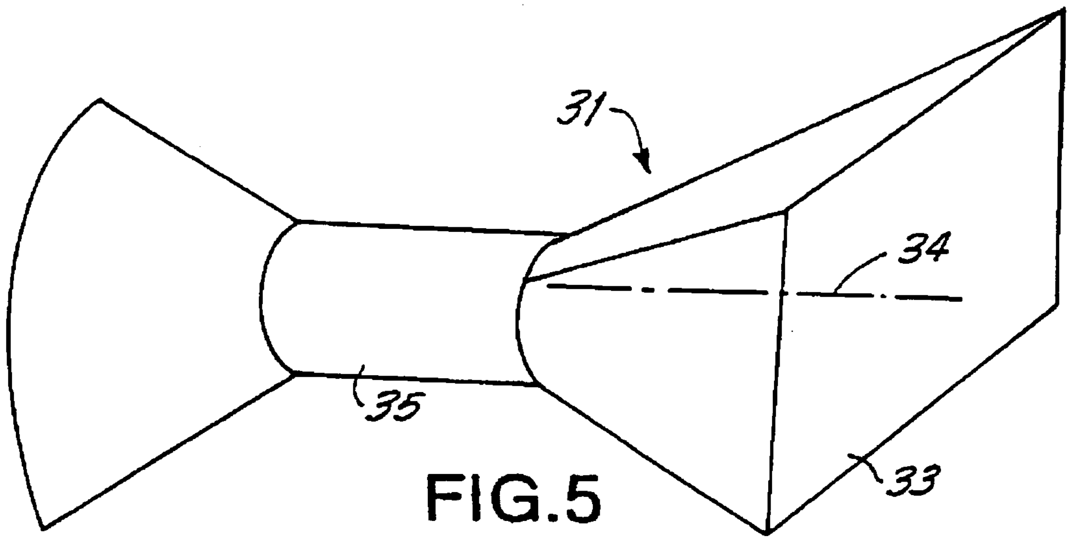


FIG.5

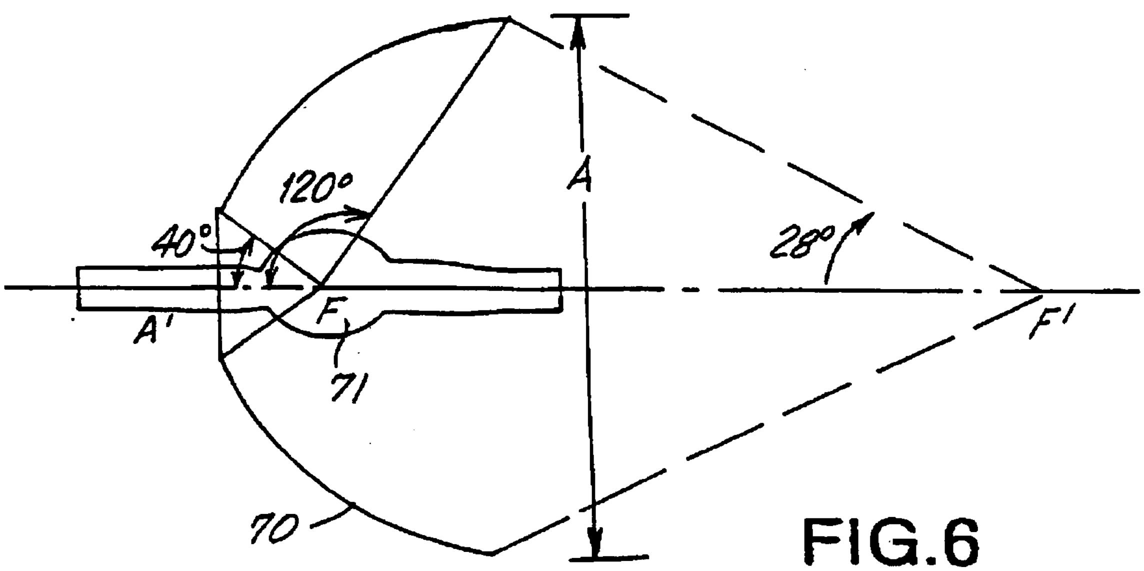


FIG.6

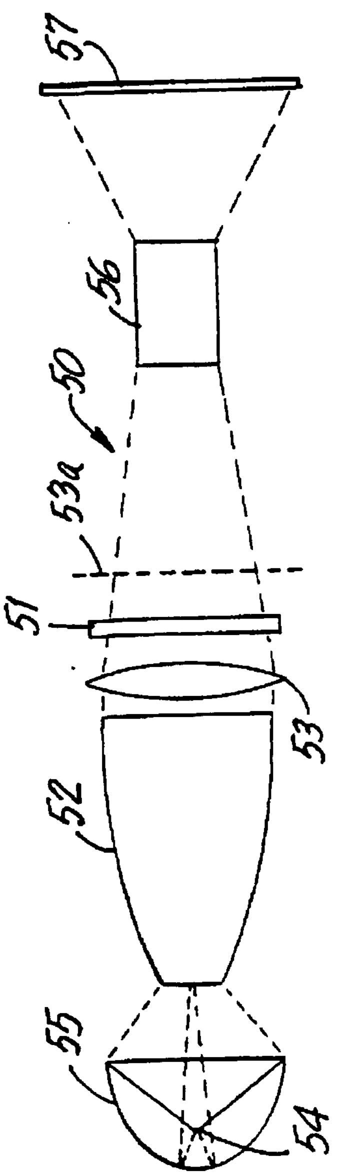


FIG.7

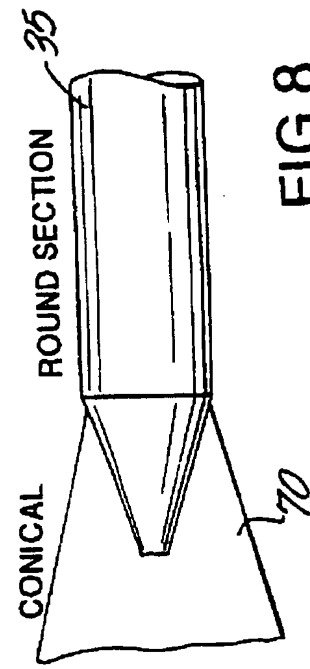


FIG.8

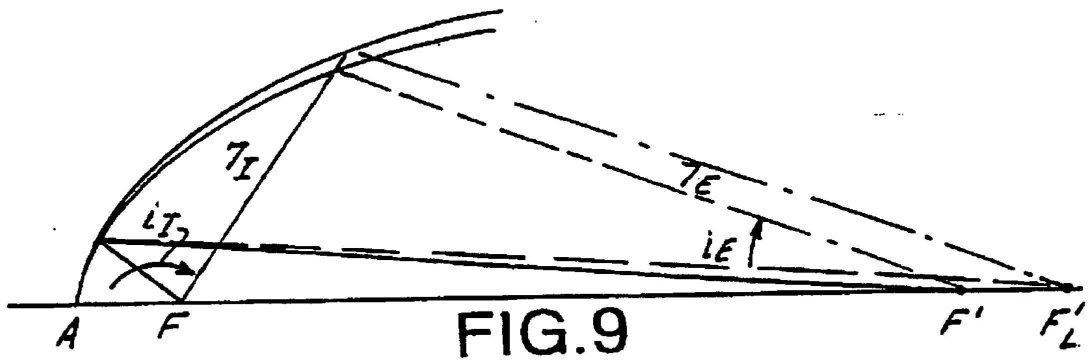

7_I
i_{I_2}
7_E
i_E
A
F
F'
F_L'

FIG.9

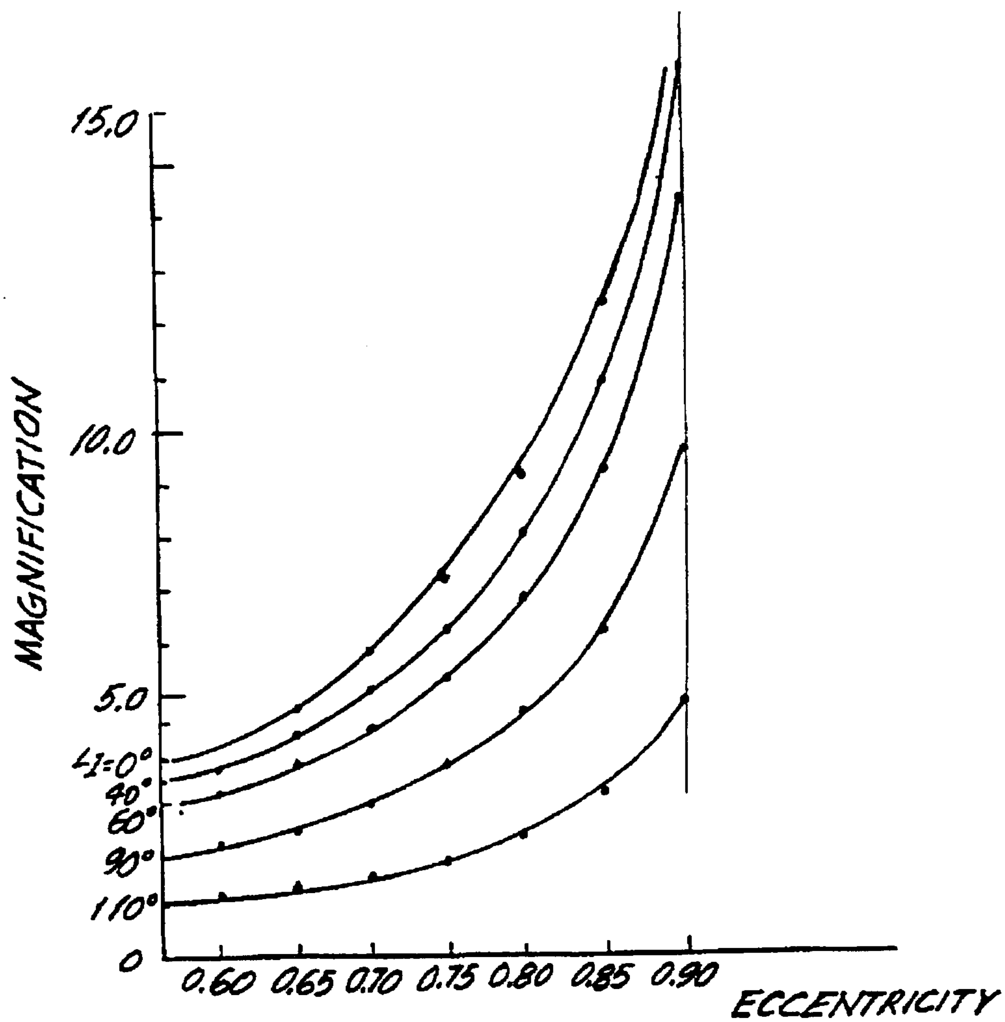

15.0
10.0
5.0
0
MAGNIFICATION
$\angle I=0°$
40°
60°
90°
110°
0.60 0.65 0.70 0.75 0.80 0.85 0.90
ECCENTRICITY

FIG.10

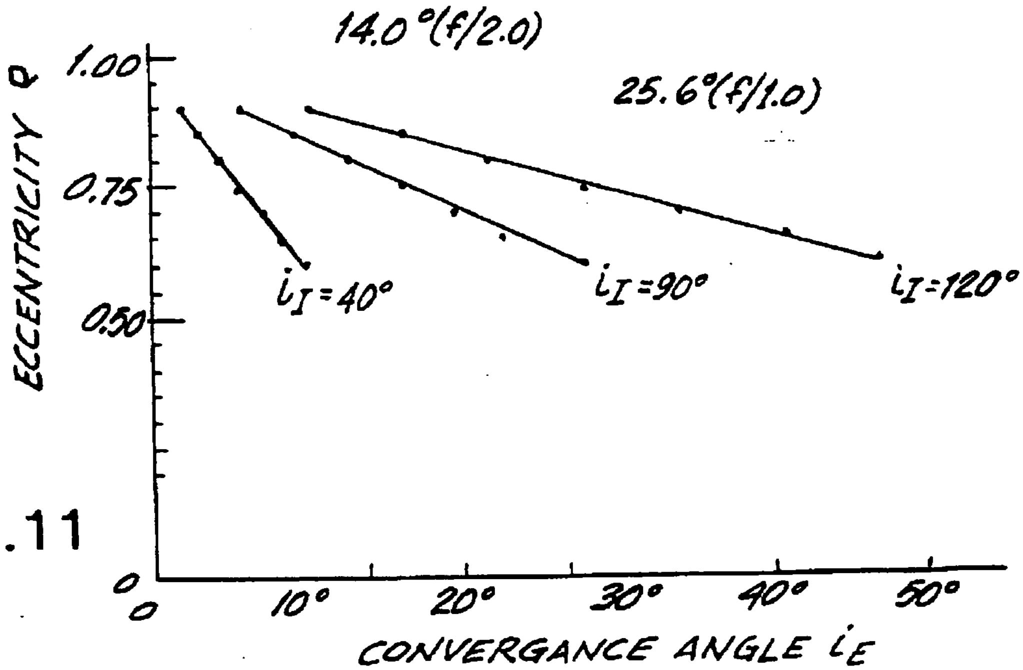

14.0°(f/2.0)
25.6°(f/1.0)
ECCENTRICITY e
1.00
0.75
0.50
0
i_I=40°
i_I=90°
i_I=120°
0
10°
20°
30°
40°
50°
CONVERGANCE ANGLE i_E

FIG.11

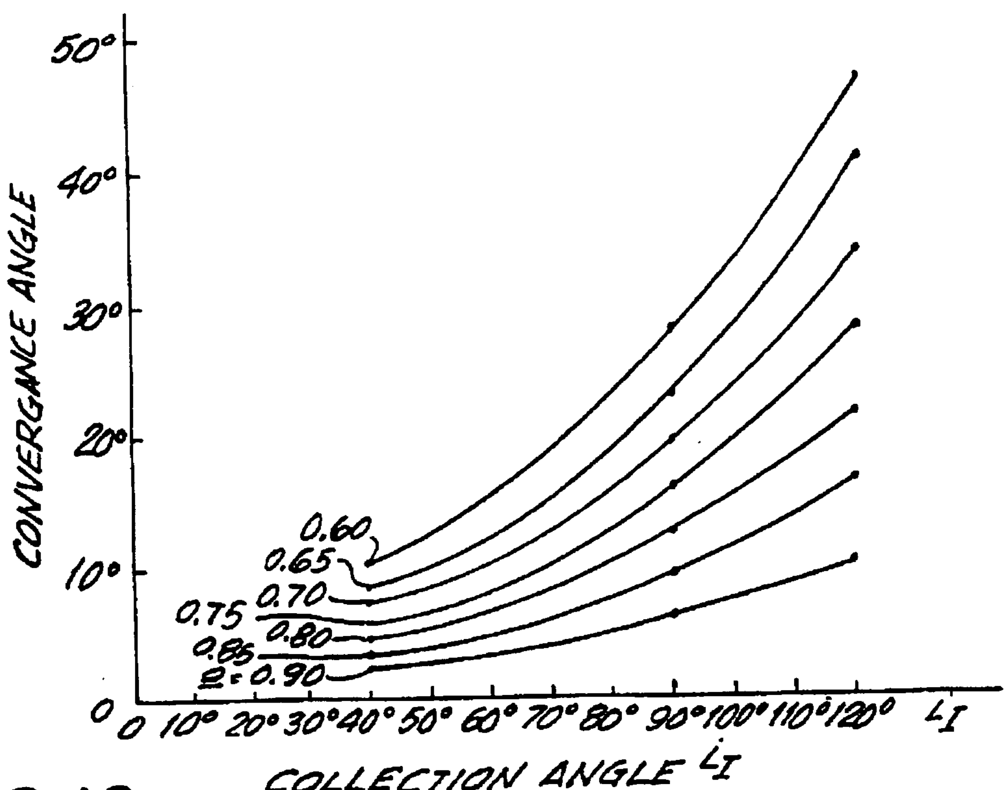

50°
40°
30°
20°
10°
CONVERGANCE ANGLE
0.60
0.65
0.70
0.75
0.80
0.85
e=0.90
0
0 10° 20° 30° 40° 50° 60° 70° 80° 90° 100° 110° 120° i_I
COLLECTION ANGLE i_I

FIG.12

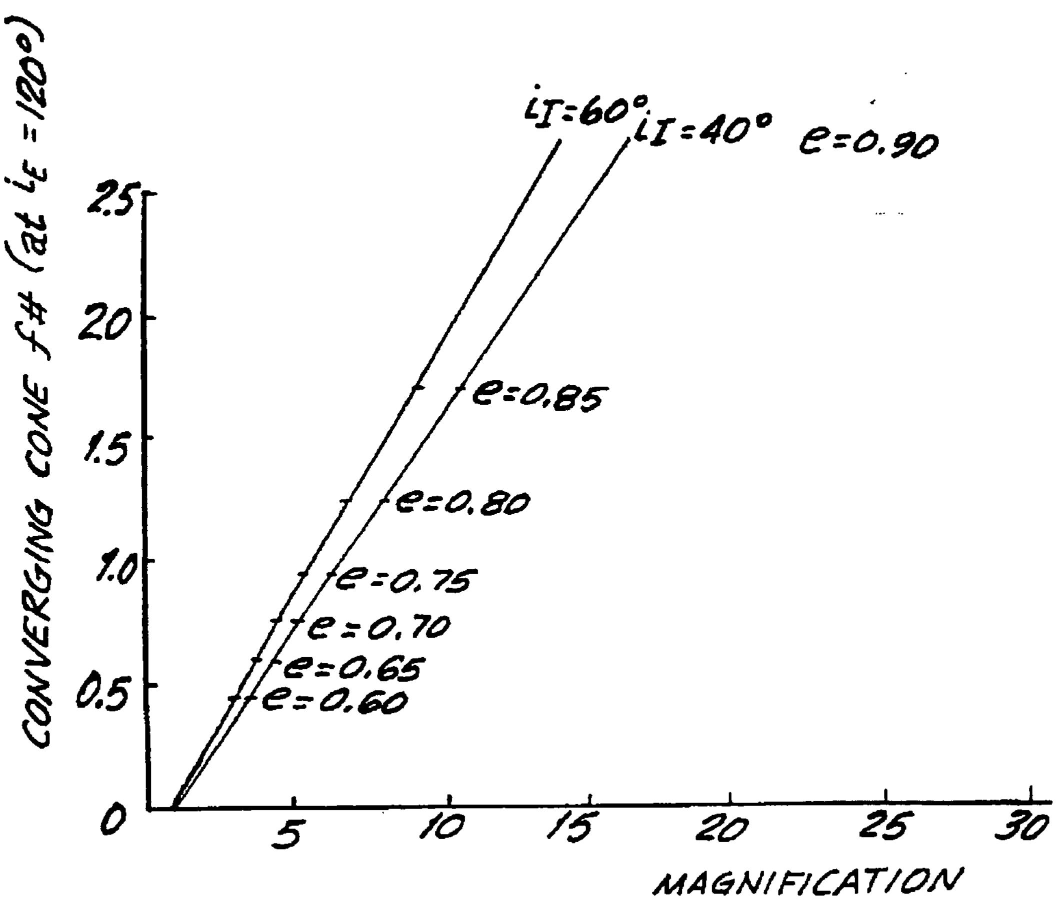

CONVERGING CONE f# (at i_E = 120°)
25
20
1.5
1.0
0.5
0
5
10
15
20
25
30
MAGNIFICATION
i_I=60°
i_I=40°
e=0.90
e=0.85
e=0.80
e=0.75
e=0.70
e=0.65
e=0.60

FIG.13

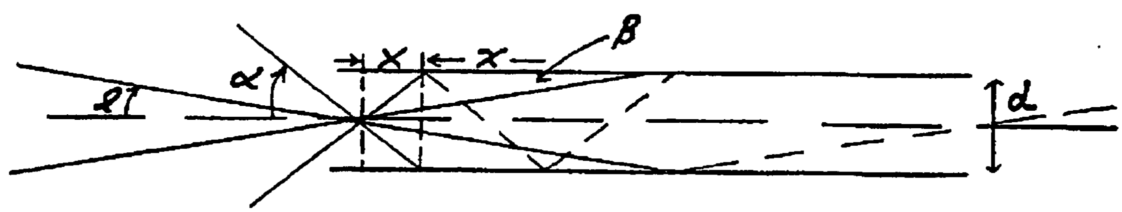
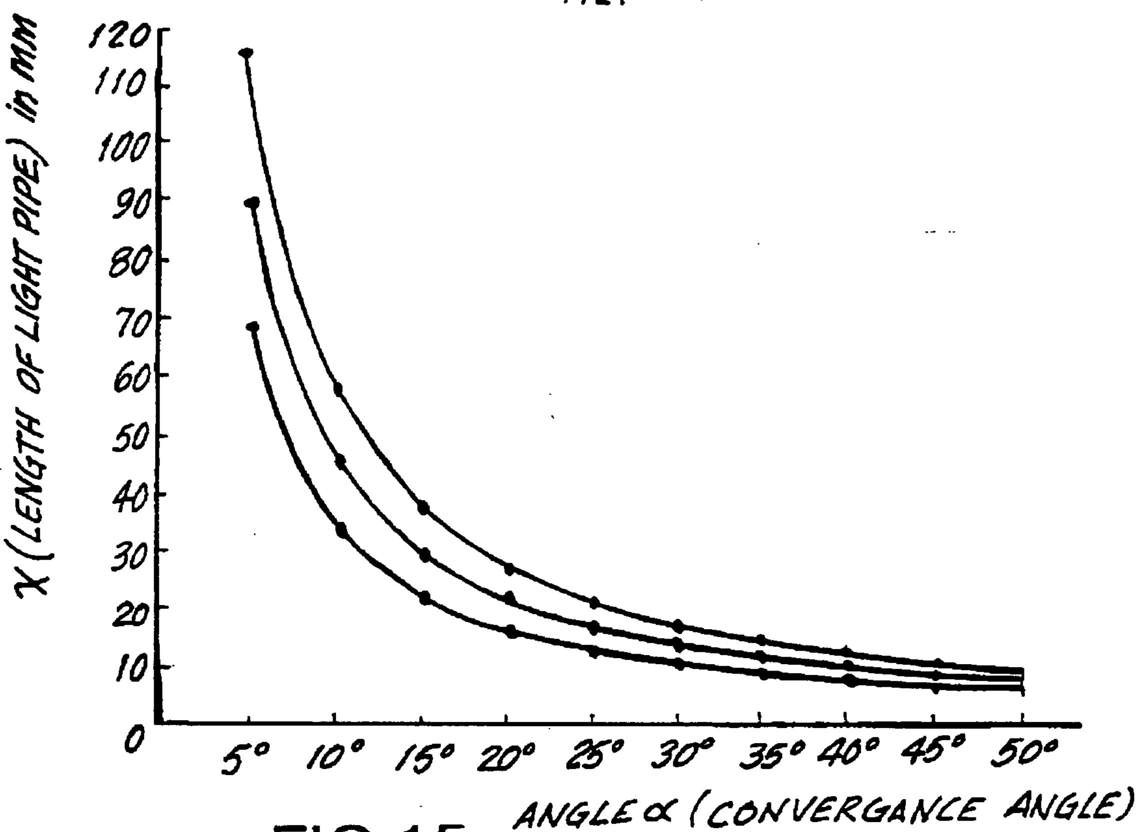
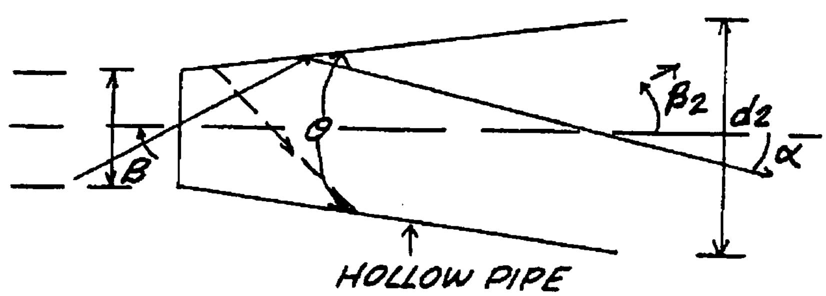

α
2I
X
x
β
d

FIG.14



X (LENGTH OF LIGHT PIPE) in MM
120
110
100
90
80
70
60
50
40
30
20
10
0
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°
ANGLE α (CONVERGANCE ANGLE)

FIG.15



β
θ
β2
d2
α
HOLLOW PIPE

FIG.16

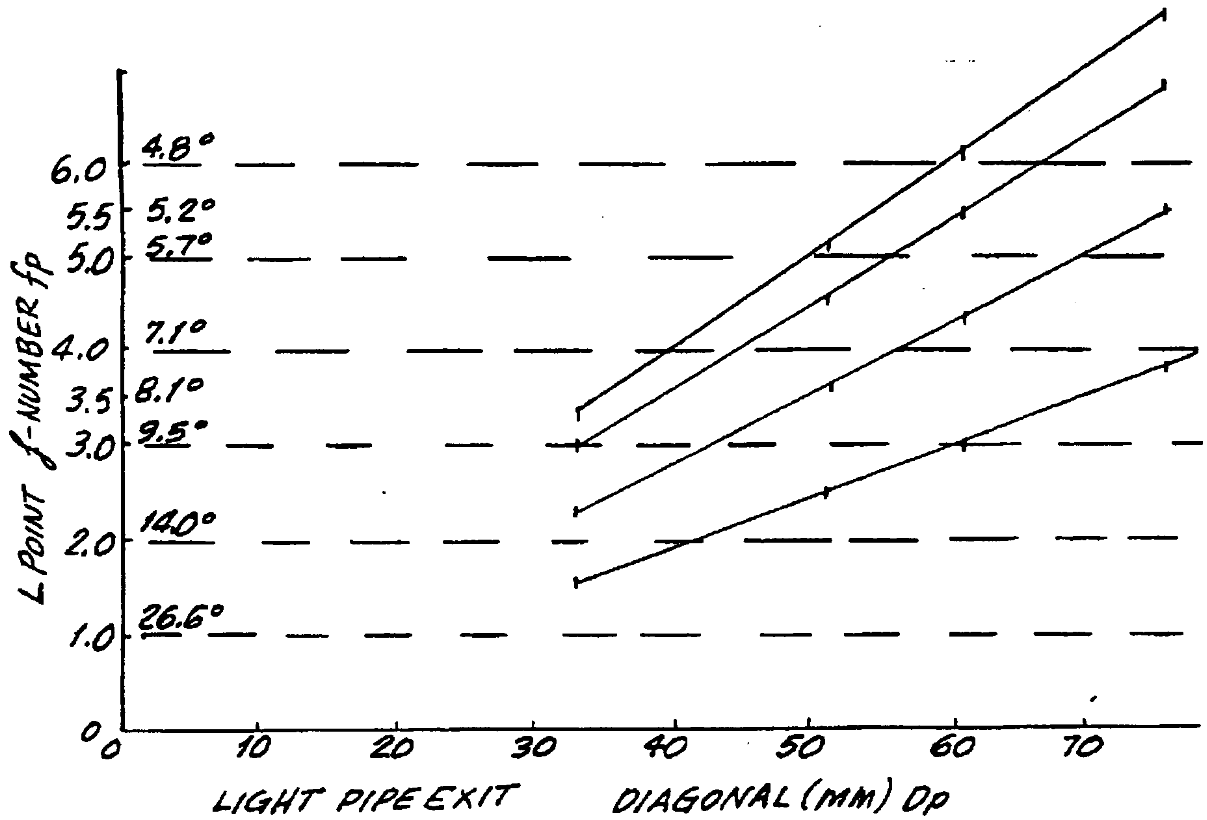

4.8°
5.2°
5.7°
7.1°
8.1°
9.5°
14.0°
26.6°
6.0
5.5
5.0
4.0
3.5
3.0
2.0
1.0
0
0
10
20
30
40
50
60
70
L POINT f-NUMBER fp
LIGHT PIPE EXIT DIAGONAL (MM) Dp

FIG.18

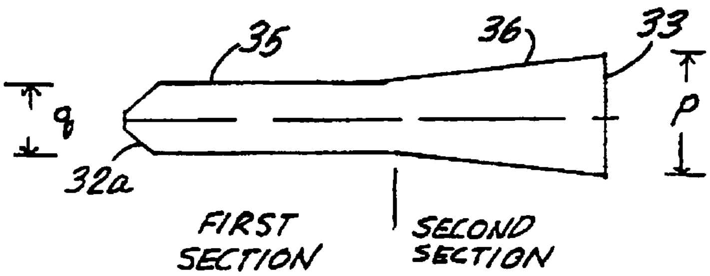

35
36
33
q
p
32a
FIRST SECTION
SECOND SECTION

FIG.19

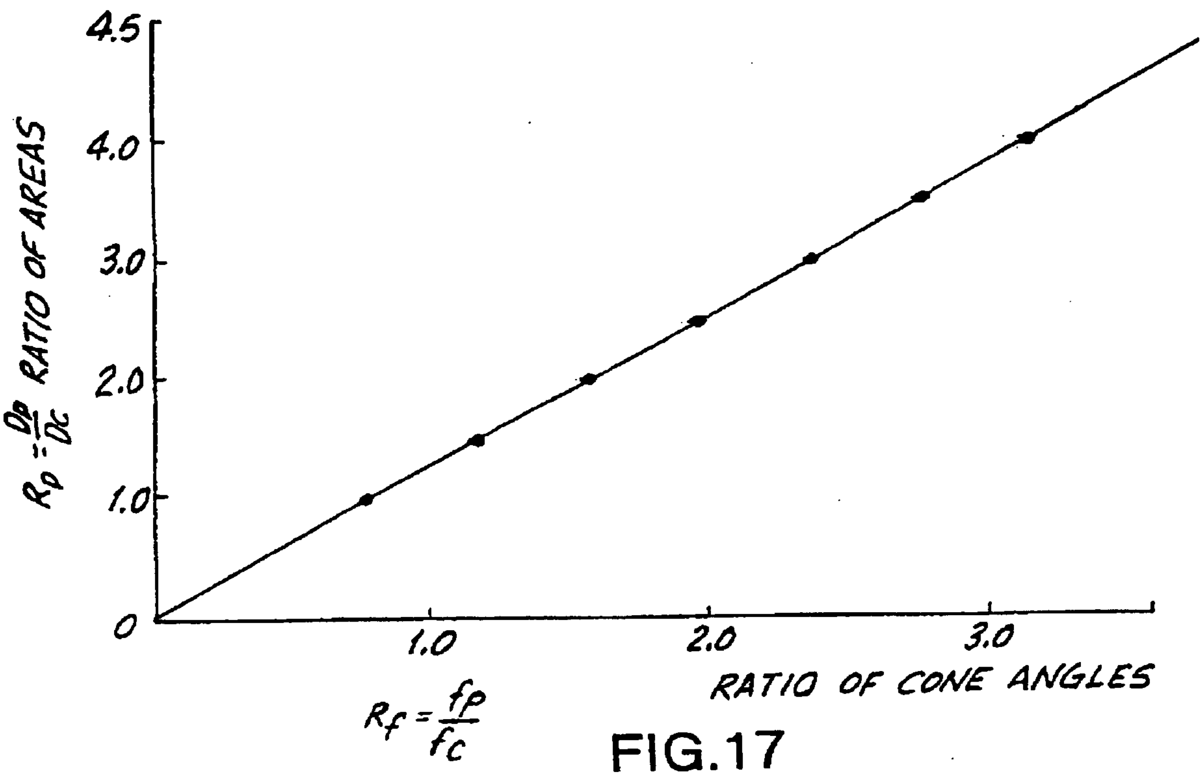

4.5
4.0
3.0
2.0
1.0
0
$R_D = \frac{D_P}{D_C}$ RATIO OF AREAS
1.0
2.0
3.0
RATIO OF CONE ANGLES
$R_f = \frac{f_P}{f_C}$

FIG.17

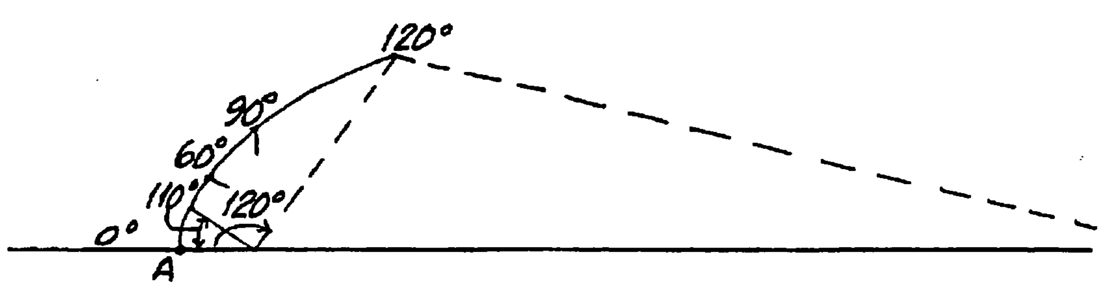

120°
90°
60°
110°
120°
0°
A

FIG.21

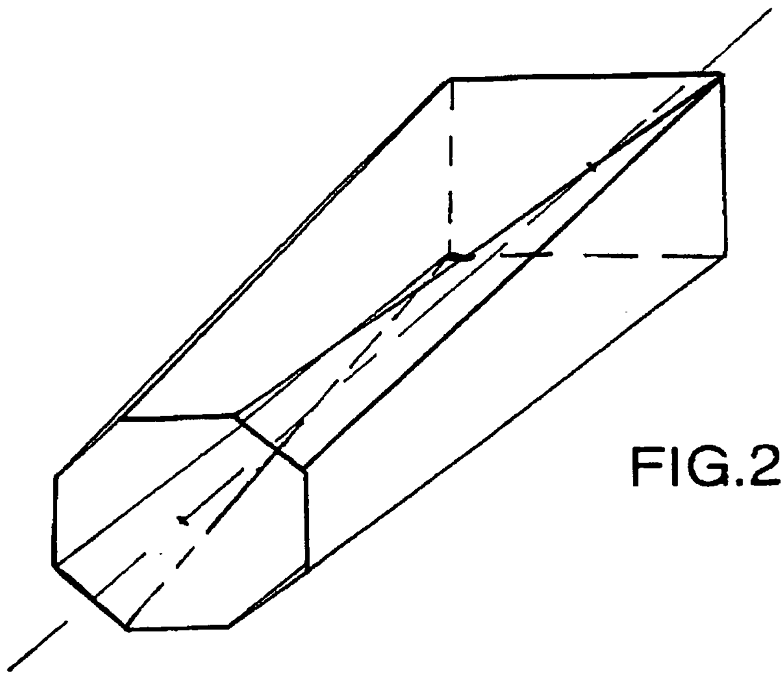


FIG.20

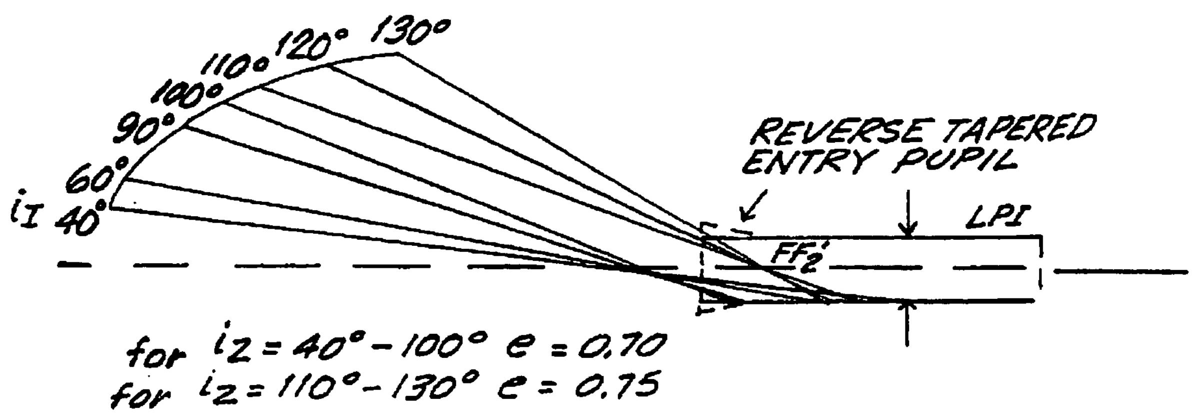

130°
120°
110°
100°
90°
60°
i_I 40°
REVERSE TAPERED ENTRY PUPIL
LPI
FF_2'
for i_Z = 40° - 100° e = 0.70
for i_Z = 110° - 130° e = 0.75

FIG.22

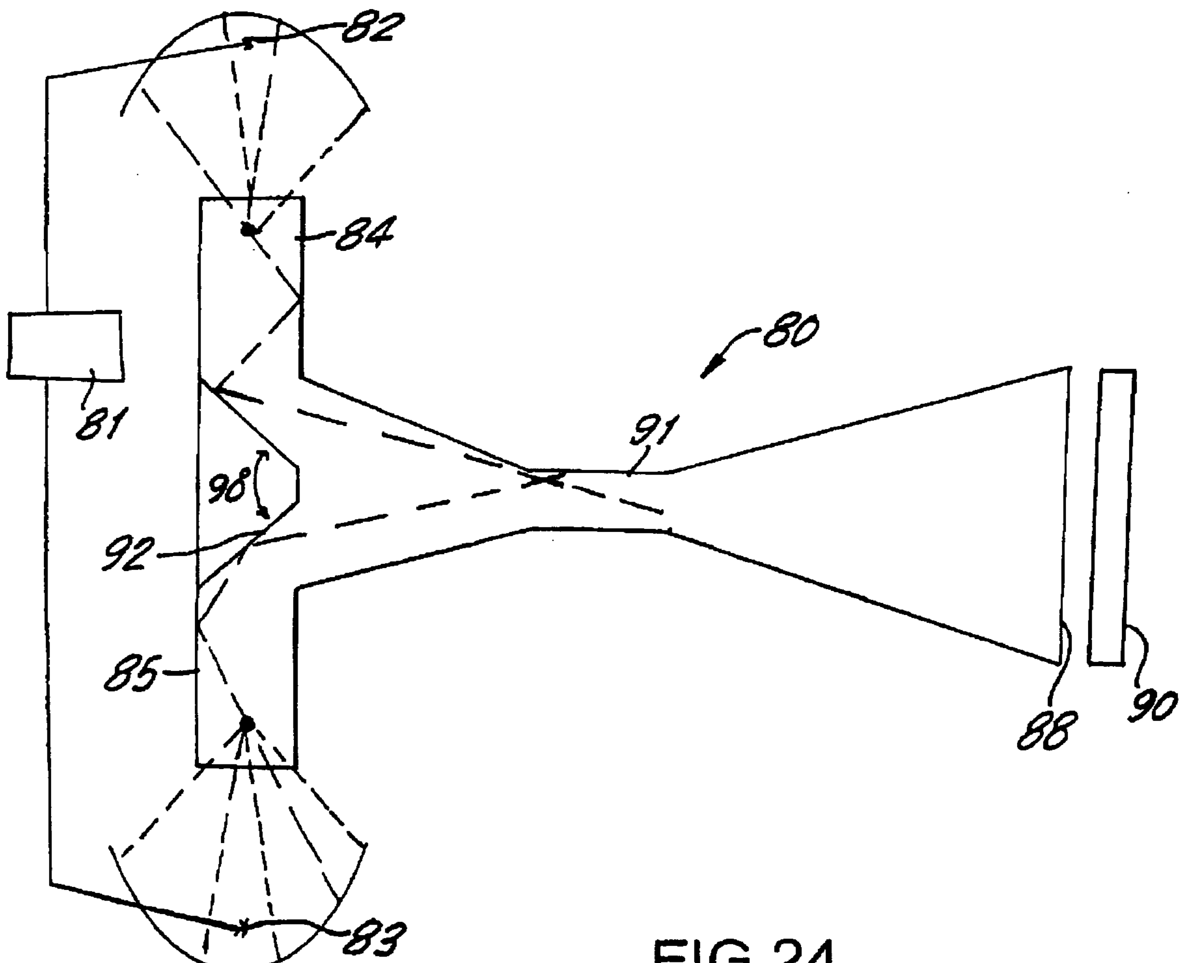


FIG.24

PANEL SIZE (diagonal in mm)	33(1.3")	51 (2.0")	76 (3.0")
ARC GAP SIZE (mm)	1.6	1.6	1.6
MAGNIFICATION at e=0.75 is ×6.2 at i(1)=40 degrees:D(i) in mm	10	10	10
TAPERED LPI DIAGONALS RATIOS R(D)	3.3	5.1	7.6
TAPERED LPI DIAGONALS MAX CONE ANGLE f# RATIO R(f)	2.6	4.0	5.9
MAXIMUM USEFUL f# at LPI in	3.5	3.5	3.5
MAXIMUM ACCEPTED f# at LPI in	1.35	0.88	0.59
MAXIMUM ACCEPTED ANGLE at LPI in (degrees)	20.3	29.6	40.3
CONE ANGLE at i(E)=120 for e=0.75 (degrees)	28	28	28
ARC GAP SIZE (mm)	3.0	3.0	3.0
MAGNIFICATION at e=0.75 is ×6.2 at i(1)=40 degrees:D(i) in mm	15	15	15
TAPERED LPI DIAGONALS RATIOS R(D)	2.2	3.4	5.1
TAPERED LPI DIAGONALS MAX CONE ANGLE f# RATIO R(f)	1.7	2.6	4.0
MAXIMUM USEFUL f# at LPI in	3.5	3.5	3.5
MAXIMUM ACCEPTED f# at LPI in	2.1	1.3	0.88
MAXIMUM ACCEPTED ANGLE at LPI in (degrees)	13.4	21.0	29.6
CONE ANGLE at i(E)=120 for e=0.70 (degrees)	34	34	34

FIG.25

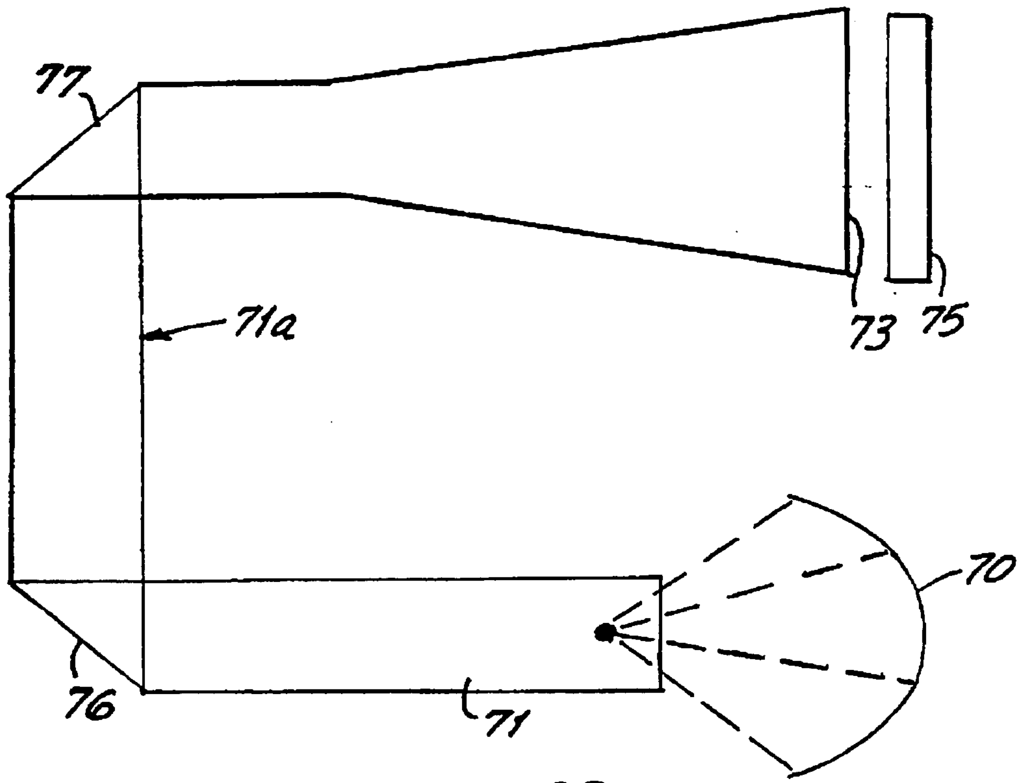

77
71a
73
75
70
76
71

FIG.23

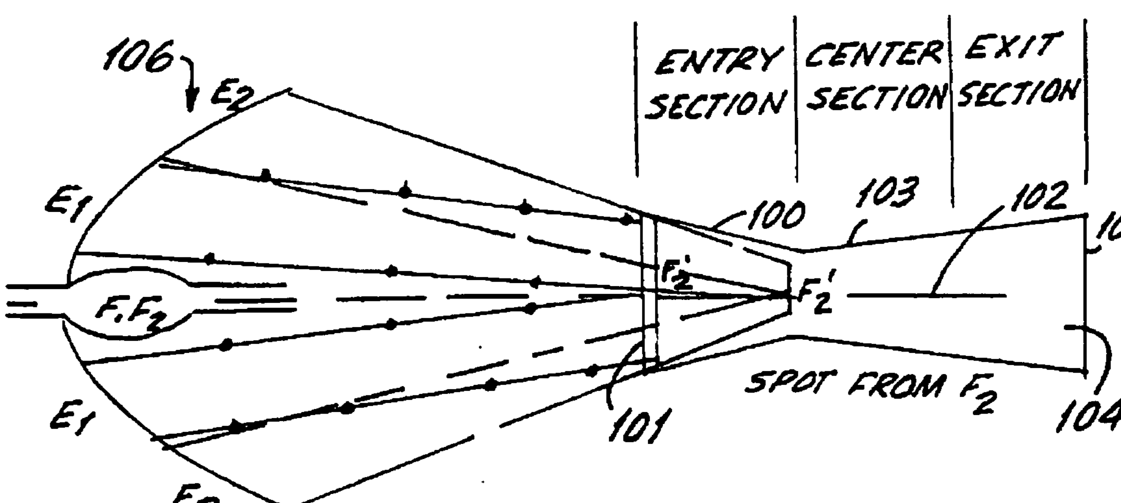

106
E_2
ENTRY SECTION
CENTER SECTION
EXIT SECTION
E_1
100
103
102
105
F_2'
F_2'
F_1F_2
101
SPOT FROM F_2
104
E_1
E_2

FIG.26

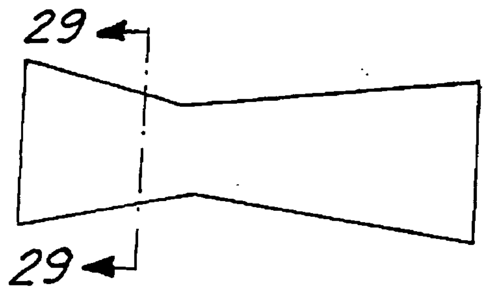


FIG.28

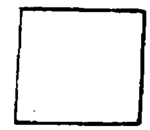


FIG.29

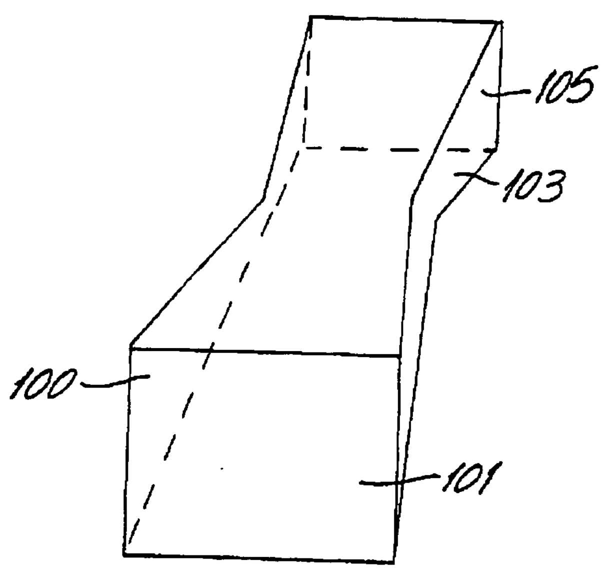


FIG.27

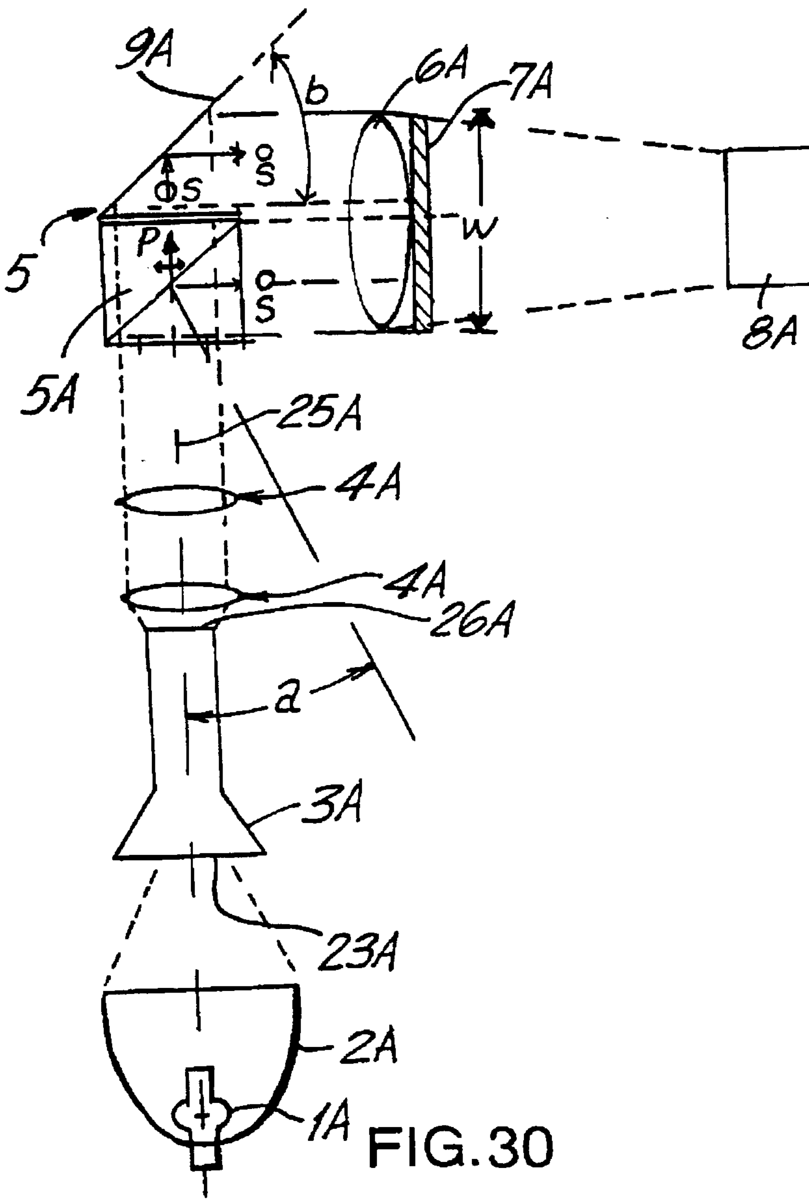


FIG.30

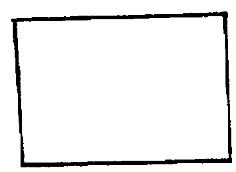


FIG.32

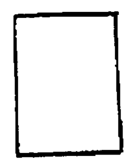


FIG.33

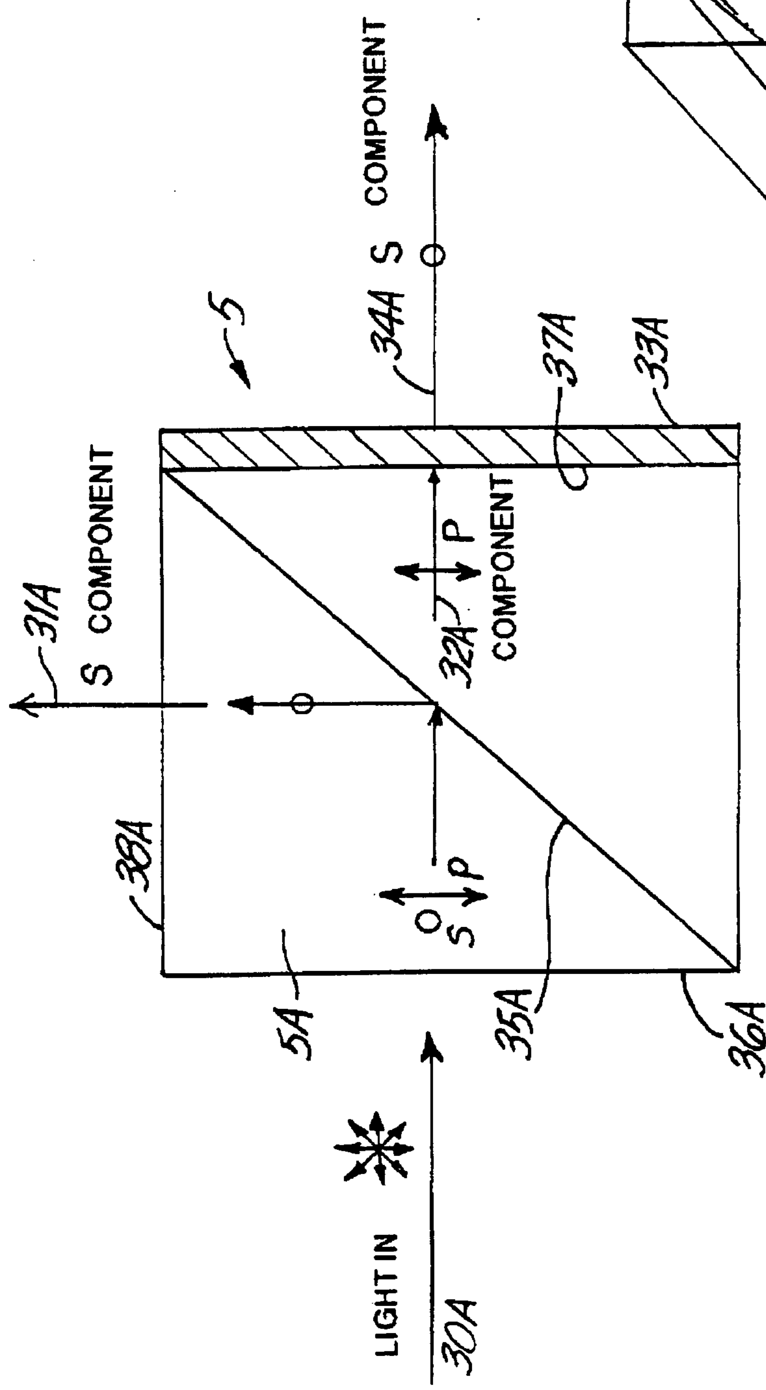

LIGHT IN
30A
5A
35A
36A
38A
31A
S COMPONENT
S
P
32A
P
COMPONENT
37A
33A
34A
5
S
COMPONENT

FIG.31

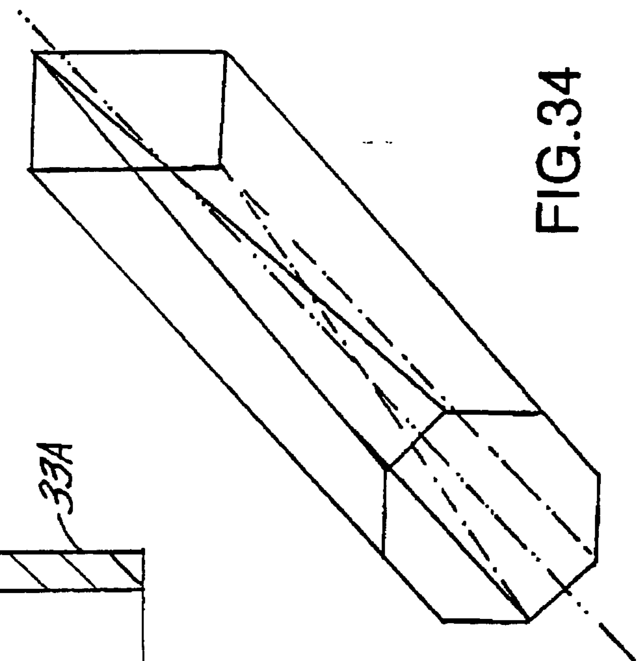


FIG.34

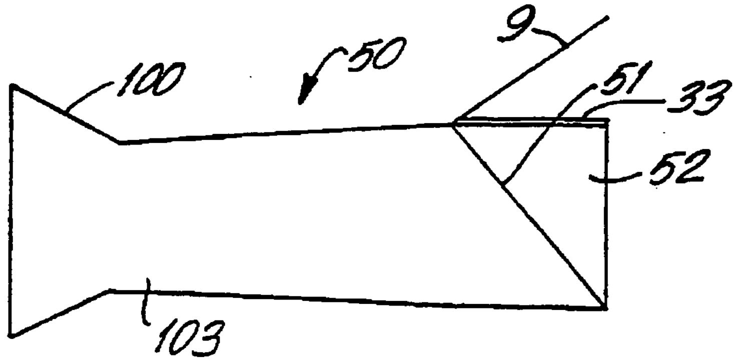
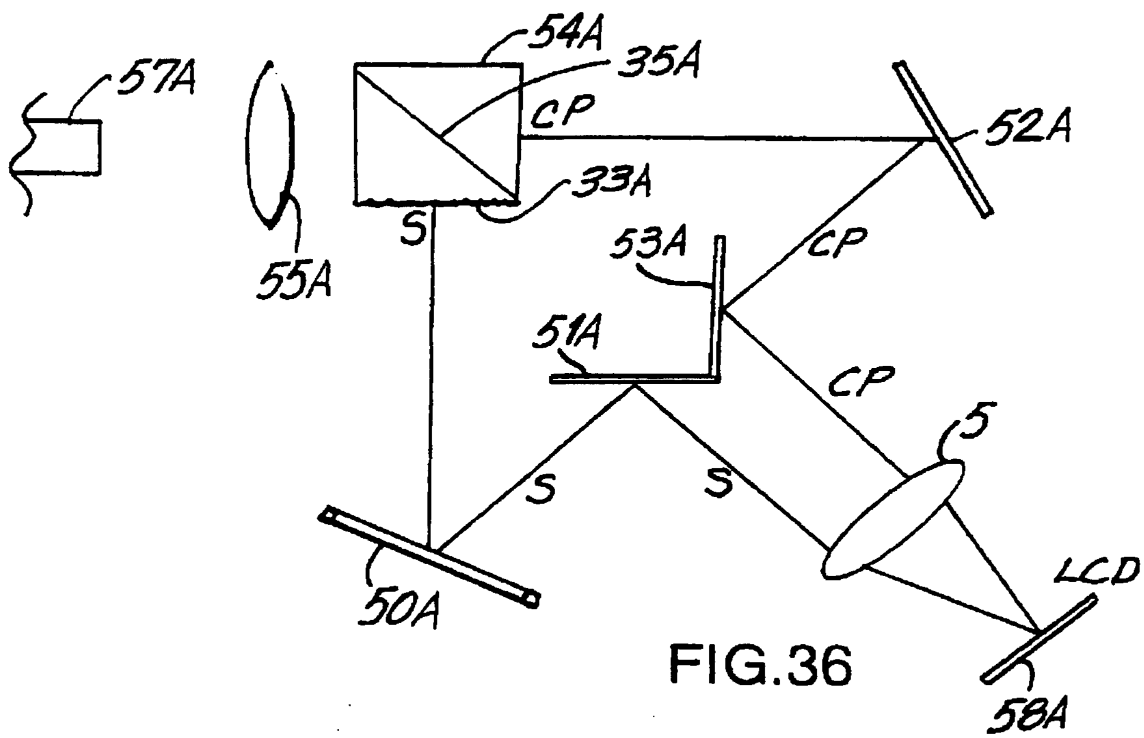

9
50
100
51
33
52
103

FIG.35


54A
35A
57A
CP
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S
55A
53A
CP
51A
CP
5
S
S
LCD
50A
58A

FIG.36

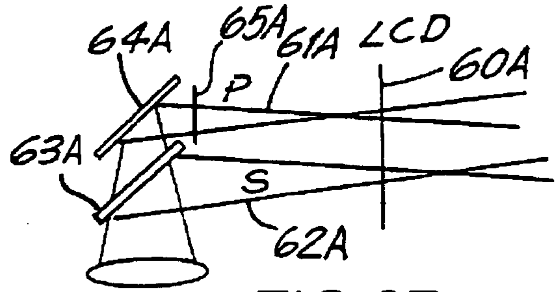

FIG.37

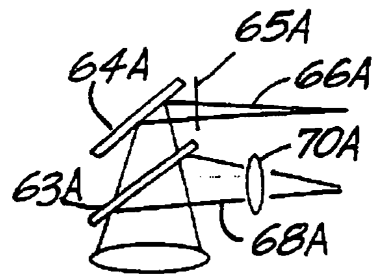

FIG.38

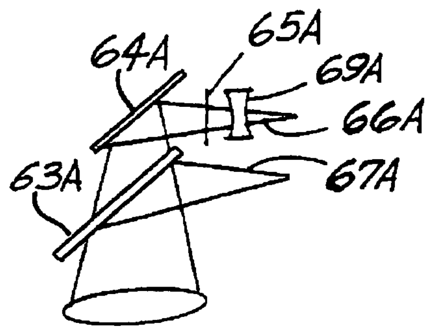

FIG.39

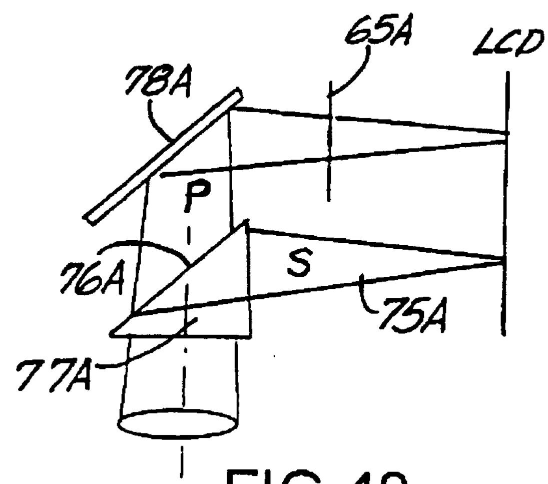

FIG.40

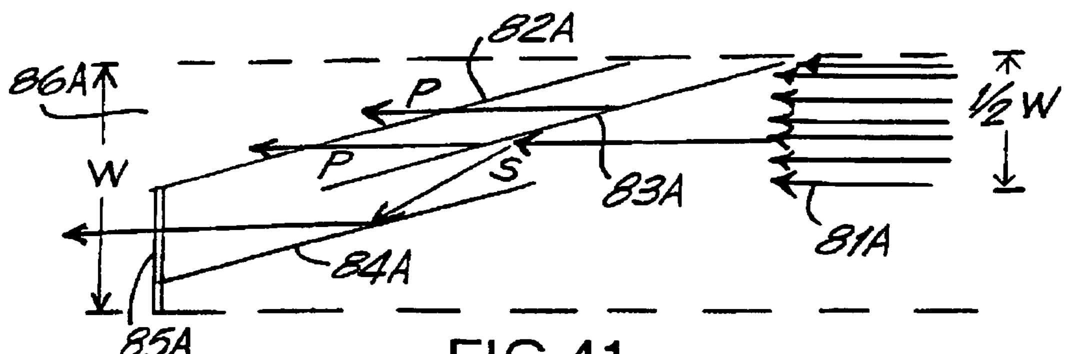

FIG.41

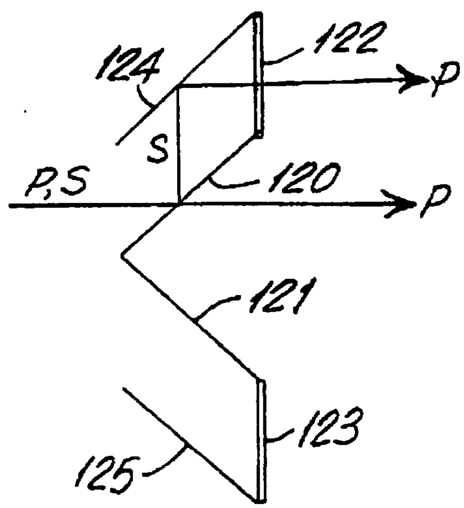

FIG.42A

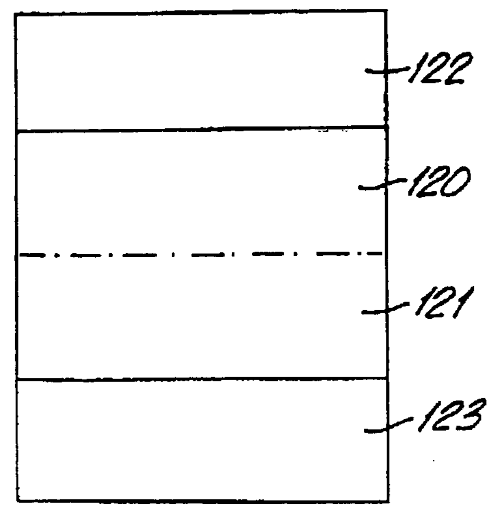

FIG.42B

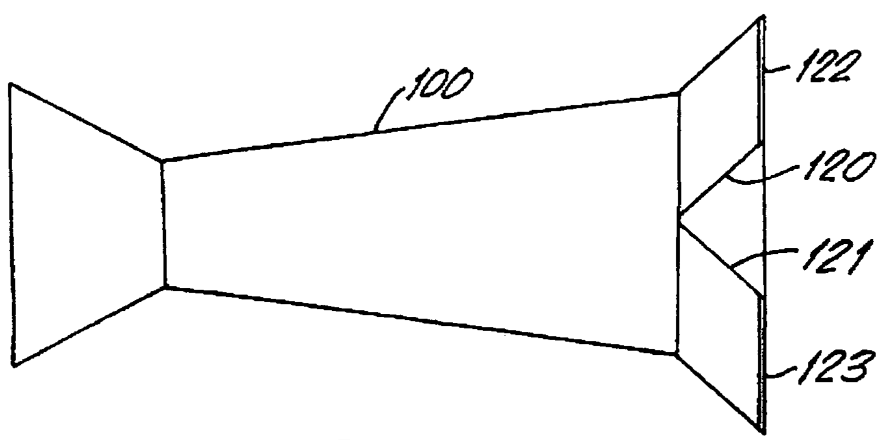

FIG.44

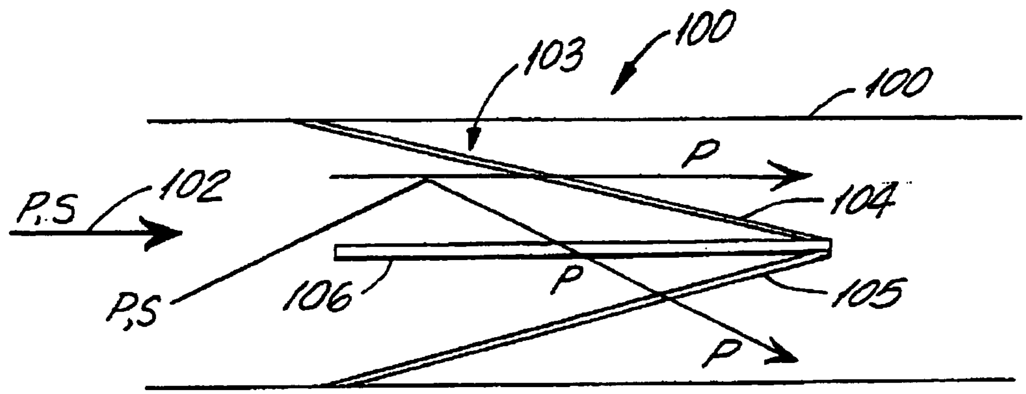

FIG.43A

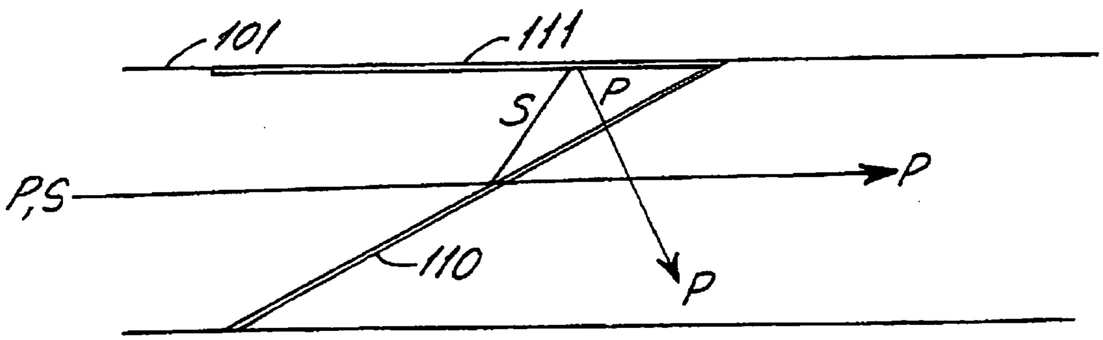

FIG.43C

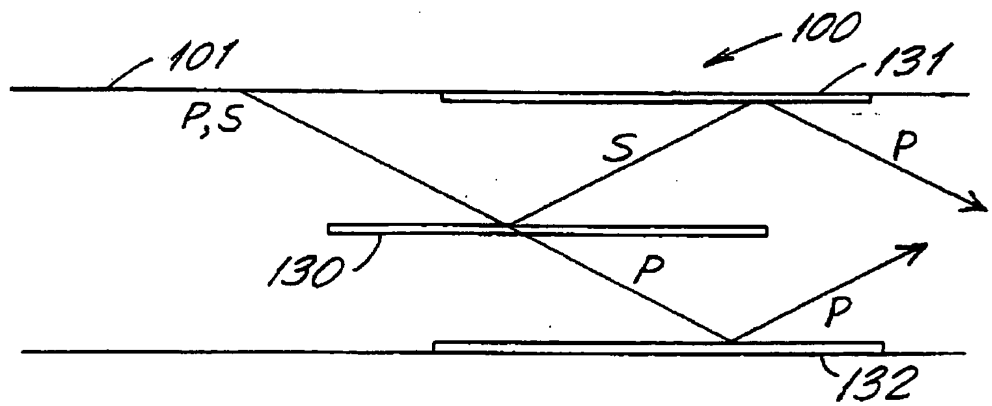

FIG.43B

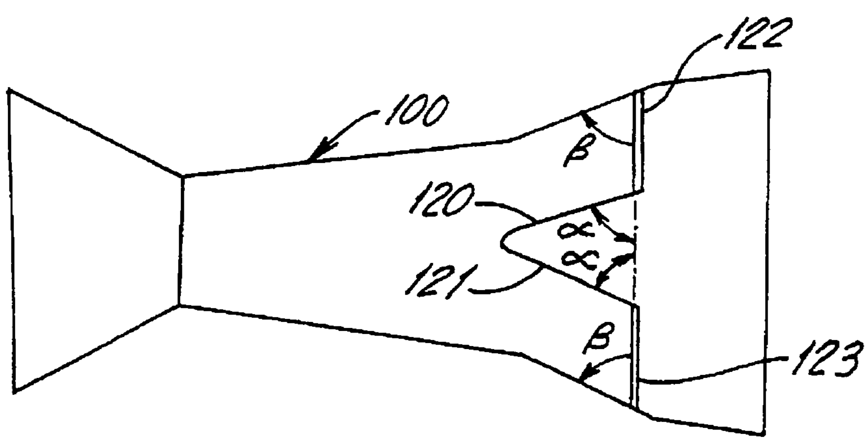

FIG.45

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/23162

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G03B 21/14
US CL : 353/98, 122; 359/894; 385/146
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 353/38, 98, 122; 359/894, 900, 503; 385/48, 123, 130, 131, 132, 146, 147

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,795,049 A (GLECKMAN) 18 August 1998 (18.08.98), see entire document.	1-40
A	US 5,634,704 A (SHIKAMA ET AL) 03 June 1997 (03.06.97), see entire document.	1-40
A	US 5,625,738 A (MAGARILL) 29 April 1997 (29.04.97), see entire document.	1-40
A	US 5,621,486 A (DOANY ET AL) 15 April 1997 (15.04.97), see entire document.	1-40
A	US 5,303,084 A (PFLIBSEN ET AL) 12 April 1994 (12.04.94), see entire document.	1-40

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search 30 JANUARY 1999	Date of mailing of the international search report 31 MAR 1999
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer WILLIAM C. DOWLING for Telephone No. (703) 308-1287

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/23162

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,059,013 A (JAIN) 22 October 1991 (22.10.91), see entire document.	1-40